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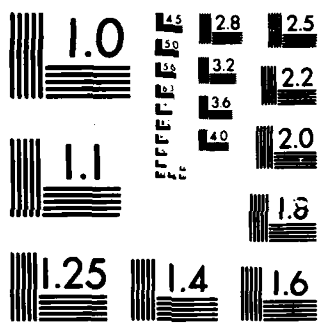

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Computed Centerline MLS Approach Demonstration at Washington National Airport

James H. Remer

October 1985

DOT/FAA/CT-TN85/63

U.S. Department of Transportation
Federal Aviation Administration

Technical Center
Atlantic City Airport, N.J. 08405

NOTICE

Technical Report Documentation Page

1. Report No. DOT/FAA/CT-TN85/63	2. Government Accession No. AD-A163722	3. Recipient's Catalog No.
4. Title and Subtitle COMPUTED CENTERLINE MLS APPROACH DEMONSTRATION AT THE WASHINGTON NATIONAL AIRPORT		5. Report Date October 1985
		6. Performing Organization Code ACT-140
7. Author(s) James H. Remer		8. Performing Organization Report No. DOT/FAA/CT-TN85/63
9. Performing Organization Name and Address Department of Transportation Federal Aviation Administration Technical Center Atlantic City Airport, New Jersey 08405		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. T0701G
12. Sponsoring Agency Name and Address Department of Transportation Federal Aviation Administration Program Engineering and Maintenance Service Washington, DC 20590		13. Type of Report and Period Covered Technical Note September 1985
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

This report covers the design, analysis, and flight test of a Computed Centerline Microwave Landing System (MLS). This system enables final approaches to be made to runways which have azimuth units offset from the runway centerline. The system was successfully flight tested at the Federal Aviation Administration (FAA) Technical Center, Atlantic City Airport, NJ, and at the Washington National Airport. Hardware design schematics and software listings are included in addition to flight test data plots.

17. Key Words Area Navigation (RNAV) Microwave Landing System (MLS) Computed Centerline Helicopter	18. Distribution Statement This document is available to the U.S. public through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	41	

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EXECUTIVE SUMMARY

This report describes the Computed Centerline Microwave Landing System (MLS) Approach Demonstration Project at the Washington National Airport. The purpose of this project was to demonstrate the capability of generating and flying a computed centerline approach for a nonstandard MLS siting. Specifically, the system which was developed enables final approaches to be made to runways which have azimuth units offset from the runway centerline. This system was successfuly flight tested at the Federal Aviation Administration (FAA) Technical Center, Atlantic City Airport, NJ, and at the Washington National Airport. Runway 33 was used at Washington, with its MLS azimuth unit situated 275 feet to the right of the centerline. Conclusions derived from this project indicate that computed centerline approaches are indeed feasible. Precautions must be taken, however, to properly tailor the course width. Site geometry and minima also impact system performance. In addition to the flight test data plots, the report contains system hardware and software design data.

INTRODUCTION

PURPOSE.

The purpose of this project was to demonstrate the feasibility of performing final approaches to a runway centerline utilizing information provided by a Microwave Landing System (MLS) which has been offset from, but of orientation parallel to the runway centerline. This capability of MLS is a significant enhancement over a conventional Instrument Landing System (ILS) which permits only straight in approaches. Computed centerline, as well as parallel and parasite approaches, of particular interest to helicopter operations are also made possible by an MLS Area Navigation (RNAV) operation. A further purpose was to assess the operability and accuracy of the system hardware and software employed in processing and displaying the MLS information in real time onboard an aircraft.

BACKGROUND.

As described in the reference, the MLS azimuth unit is offset 275 feet from runway 33 and, therefore, attempts to use conventional raw MLS information would provide guidance to a point which is located 275 feet to the pilot's right of the runway. Guidance to the runway centerline can only be provided by processing the raw MLS and Precision Distance Measuring Equipment (DME/P) information before display to the pilot. In essence, a correction factor is computed for subtraction from the raw MLS azimuth angle. An algorithm to perform this correction was developed in-house. The algorithm runs on a PDP-11/34M minicomputer and drives the course deviation indicator (CDI) and vertical deviation indicator (VDI) displays via in-house developed interface circuitry. The entire system was flight tested in a Sikorsky S-76 helicopter both at the Federal Aviation Administration (FAA) Technical Center and at the Washington National Airport. Live flight data, both visible and digital, were acquired. System performance was completely successful.

DISCUSSION

GROUND EQUIPMENT DESCRIPTION.

The Bendix MLS consists of an azimuth (AZ) system, an elevation (EL) system and a Prototype DME/P. The AZ system gives proportional horizontal guidance to $\pm 10°$ about the phase center of the antenna. From 10° to 40° on each side, there is a full fly left or fly right signal to direct the aircraft to the proportional guidance area. The EL system gives proportional vertical guidance from 1° to 15°. The Prototype DME/P is a modified Cardion DME/P. When used in conjuction with the airborne DME/P equipment, distance to the DME/P antenna from the aircraft is determined by the airborne equipment.

The azimuth antenna is installed at the runway 33 stop-end, 275 feet to the left of centerline (pilot's right). It is situated so the 0° azimuth angle is parallel to the runway centerline. A 2.0° left azimuth approach will intersect the runway centerline extended 2,663 feet outside the threshold. The elevation antenna is located 258 feet inside the threshold and 250 feet to the left of runway centerline (pilot's right). It is sited for a 35-foot threshold crossing height on a 6.0° glidepath. For a glide slope of 4.6° as flown in the present tests, this corresponds to a threshold crossing height of 26 feet.

The Prototype DME/P antenna is mounted on the top of the AZ antenna enclosure. A diagram of the runway 33 installation is shown in figure 1.

AIRBORNE EQUIPMENT DESCRIPTION.

The principal constituents of the airborne equipment are the MLS angle receiver, DME/P interrogator, and Norden PDP-11/34M minicomputer with associated input/output (I/O) interfaces (see simplified block diagram in figure 2). A PDP-11/34M was utilized because it was a readily available existing system which also performs data acquisition tasks. It had more computational power than required for the algorithm, which could have run equally well on a microcomputer such as the Intel 8086. The MLS angle receiver provides digital outputs of the AZ (θ) and EL (ϕ) angles. Along with the DME/P digital range word (ρ) these data words are transmitted to the MLS and DME/P digital interfaces in the system I/O card cage. From the I/O cards, the data are put on a digital aircraft systems coupler (ASC) bus for transmission to the PDP-11/34M computer. The minicomputer processes these data using the algorithm documented under the software description. The processed AZ and EL angles are then sent in digital form over the ASC bus to the digital-to-analog converter card. There, they are converted to -150 to +150 microamp full scale analog signals to drive the pilot and flight technician's CDI and VDI. This card also contains watch dog timers to drop the flags if guidance is absent for 2 seconds or longer (flag bits ride high order on the data words). The update rate to the displays is set at a 4 hertz (Hz) rate. When not providing computed centerline AZ values, the computer also serves as the controller of a data acquisition system. On-board data is recorded by this system on a Quantex cartridge tape recorder. A detailed block diagram of this hardware is included as figure 3. Unlabeled blocks represent modules of a full MLS RNAV system which were not used in this application.

SOFTWARE AND ALGORITHM.

The program resident in the airborne PDP-11/34M computer system, which controls data acquisition and the processing of the raw MLS data, is written in the FORTRAN language. The computational burden of this program is minimal. It comprises less than 50 lines of executable code. This program was developed on a laboratory PDP-11/34 computer, transferred to 8 inch floppy discs, and then loaded into the airborne PDP 11/34M computer system. At the heart of this program is an algorithm which computes the AZ angular offset error and then subtracts it from the raw AZ angle in order to arrive at a computed centerline based AZ angle. In order to compute this angle, raw AZ, EL, and DME/P data are used. The DME/P defines a sphere of radius (ρ), the AZ a vertical plane at angle (θ) referenced to boresight, and the EL a cone of angle (ϕ). The intersections of these surfaces, as shown in figure 4, defines 4 points in Cartesian x,y,z space. Three of these points can be discarded from a prior knowledge of our quadrant in space (above ground, no back azimuth). The equations which result are:

From DME/P: $x^2 + y^2 + z^2 = \rho^2$ (1)

From Azimuth: $x = y\tan\theta$ (2)

$$\text{From EL:}\quad x^2 + (y-ye)^2 = z^2\cot^2\phi \tag{3}$$

These equations are solved for y and a quadratic equation in y results as follows:

$$y^2(\tan^2\theta + \cot^2\phi + \tan^2\theta\cot^2\phi + 1) - 2yye - \rho^2\cot^2\phi + y^2e = 0 \tag{4}$$

This is solved for y using the quadratic formula and results in:

$$y = \frac{2ye \pm (4ye^2 - 4(\tan^2\theta + \cot^2\phi + \tan^2\theta\cot^2\phi + 1)(ye^2 - \rho^2\cot^2\phi))^{1/2}}{2(\tan^2\theta + \cot^2\phi + \tan^2\theta\cot^2\phi + 1)}$$

The y value obtained from equation 5 is then used in calculating the correction angle θ_c as follows:

$$\theta c = \tan^{-1}\frac{(275\text{ ft})}{y} \tag{6}$$

The final processed azimuth value of θ is obtained by subtracting the correction angle θ_c.

$$\theta_{TRUE} = \theta_{RAW} - \theta_c \tag{7}$$

Other key modules of the software are the gain programming feature (or sensitivity modulation) for the course deviation displacement. Sensitivity modulation is necessary due to the increased sensitivity which results at ranges close to the AZ unit. This problem is attributable to the increased rate at which radials are cut at the close-in ranges. Although no loss of MLS or DME/P signal occurred throughout the test, coasting was necessitated by the possible loss of MLS and DME/P data or by a breakdown and/or singularity in the error angle algorithms. Coasting was accomplished by holding and outputting the last valid computed point until a time out period has elapsed (2 seconds), at which time the display flags are dropped.

Sensitivity modulation was accomplished by linearizing the course width within 3 nautical miles slant range of the AZ antenna. Beyond 3 miles slant range full scale CDI displacement represents a ±2.5° deviation from centerline. Between 3 nautical miles and the runway threshold (0.86 nautical miles) the sensitivity is linearly decreased so that a 350-foot displacement from the centerline represents a full scale deflection. This sensitivity is equivalent to ±3.84° full scale deflections if the AZ is located on the runway centerline. The threshold sensitivity is equivalent to standard ILS sensitivity. The AZ course width tailoring is presented in figure 5.

A listing of the software required for the computed centerline test is presented in figure 6.

TEST PROCEDURES.

Airborne tests of the MLS computed centerline system were conducted using the Technical Center's S-76 helicopter (N-38). Initial system tests were conducted at the Technical Center using the Bendix MLS located on runway 31. Here the

offset of the MLS was simulated by flying 250-300 feet to the side of the runway. Subsequent system test flights were conducted at Washington National by flying numerous approaches to runway 33. These approaches included straight-in approaches with raw MLS and with computed centerline processing. The EL angle used on all approaches was 4.6°. Final approach speed varied from 80 to 120 knots.

Airborne data were collected using both video tape for visual information and digital data on cartridge tape for instrumentation purposes. The update rate of the computer/data acquisition system was chosen to be 4 Hz. This proved sufficient for piloting and recording purposes.

DATA PROCESSING.

As discussed previously, airborne data, which includes crosstrack distance, raw and computed AZ deviation, height above field, EL deviation and along - track distance was recorded on an airborne Quantex cartridge digital tape recorder. The cartridge tape with its raw digital data was then processed in the laboratory into a conventional 1/2 inch 9 track data tape format compatible with the Digital Equipment Corporation RT-11 operating system. This tape was then subjected to a merge process, with the distinction that range data (radar, laser, etc.) were not present.

Finally, the merged file was outputted to a Calcomp plotter which produced graphical output. All of the forgoing operations were performed on a Digital Equipment Corporation PDP-11/34 minicomputer.

DATA ANALYSIS DESCRIPTION.

A compendium of all approaches made to runway 33 at the Washington National Airport in aircraft N-38 using MLS computed centerline technology is included in table 1. Runs 1 through 9 are included in the data, with runs 8 and 9 flown to touchdown. All approaches were made at an EL angle of 4.6°, but various approach speeds were flown. Data from all runs were processed as described in "Data Processing" and then plotted via a Calcomp plotter. Two plots are provided for each data run. The first plot of each set provides AZ information. Parameters plotted are AZ deviation in microamps, computed AZ deviation in microamps, and crosstrack distance in feet, all as a function of along-track distance. The second plot of each set provides EL information. Parameters plotted are EL deviation in microamps and height above field, both as a function of along-track distance. Plots for runs 1 through 9 inclusive are presented in figures 7 through 25.

The graphs of the principal parameter of interest, crosstrack distance from runway centerline, reveal a striking ability to maintain track on the extended centerline within the tailored course width for the approaches flown. The computed centerline system was able to guide the aircraft to touch down to within 4 feet of the centerline on the final approach, run 9 (figure 23). The functioning of the system is demonstrated graphically by comparison of raw azimuth and computed azimuth deviation current. Currents of ± 150 microamps correspond to full course width deviations and are shown as horizontal lines on the CDI plots. This comparison reveals that both curves are congruent, however, the raw azimuth is shifted by a negative bias current which is

TABLE 1. COMPUTED CENTERLINE APPROACHES WASHINGTON NATIONAL AIRPORT

Run #	A/C	Date 1985	Indicated Airspeed (kts)	Elev. (deg)	Wind (deg/kts)	Baro (In. Hg.)	Start Time (H:M:S)	Stop Time (H:M:S)
1	N-38	July 23	80	4.6	310/08	30.07	10:12:56	10:16:05
2	N-38	July 23	80	4.6	310/08	30.07	10:19:00	10:23:32
3	N-38	July 23	100	4.6	310/08	30.07	10:26:46	10:30:07
4	N-38	July 23	90	4.6	34/06	30.07	11:52:57	11:57:06
5	N-38	July 23	90	4.6	34/06	30.07	12:33:01	12:36:04
6	N-38	July 23	120	4.6	34/06	30.07	12:38:39	12:41:20
7	N-38	July 23	90	4.6	31/13	30.07	12:49:52	12:52:14
8*	N-38	July 23	90	4.6	31/13	30.07	12:55:09	12:57:47
9*	N-38	July 23	90	4.6	31/08	30.07	13:02:38	13:05:52

*Flown to Touchdown

subtracted out in the computed azimuth to yield a symmetrical path about the extended centerline. A tabulation of the mean and standard deviation for each run is included as table 2. Composite plots of the nine data runs have been produced in the same format as for individual runs. These are presented in figure 26. Comparison of both azimuth and elevation tracking data reveals the increasing ability to fly the computed centerline system as the pilot gains familiarity with it.

CONCLUSIONS

1. Offset computed centerline line approaches using Microwave Landing System (MLS) Precision Distance Measuring Equipment (DME/P) data are feasible.

2. Course width tailoring is required and is dependent on the baseline distance between the azimuth (AZ) and elevation (EL) sites, the amount of offset of the AZ site, and approach minima.

3. The data rate required to provide smooth needle display is a function of several variables including:

    a. The baseline distance between the azimuth and elevation antenna sites.

    b. The approach minima. Further investigations of the minimum data rates required to support raw data display of computed centerline information are required.

4. Pilots had no difficulty in flying the computed centerline approaches when the course width was tailored as shown in figure 5.

5. Analytical and experimental studies need to be conducted in order to establish total system accuracy criteria needed to meet published minima in Federal Aviation Administration (FAA) Advisory Circular (AC) 90-45A.

REFERENCES

Townsend, John E., "Engineering Flight Tests on the Bendix Small Community MLS, Runway 33, Washington National Airport", FAA Technical Center Letter Report CT-82-100-102LR, September 1982.

TABLE 2. FLIGHT TEST DATA STATISTICS

Run #	Samples	Velocity (kts)	Azimuth Mean (1)	Azimuth Standard Deviation (1)
1	259	80	-0.02422	0.06355
2	227	80	-0.0562	0.0739
3	283	100	-0.0140	0.0747
4	239	90	-0.0654	0.2293
5	221	90	-0.01738	0.1126
6	127	120	+0.0437	0.08105
7	245	90	-0.0276	0.0927
8	301	90	-0.0361	0.1096
9	311	90	-0.02587	0.0925

(1) Expressed as a percentage of $\pm$ 150 microamps full scale current.

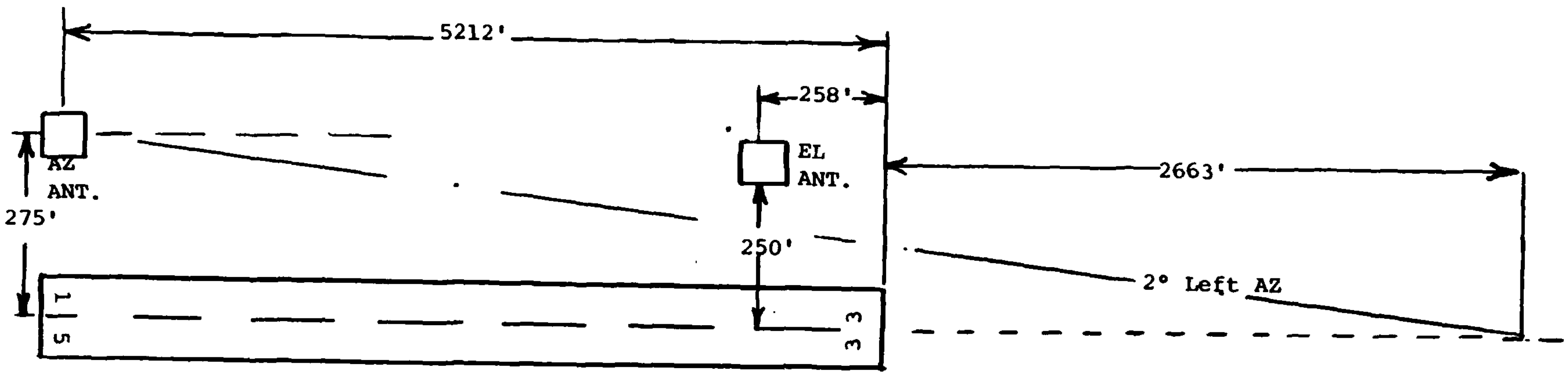


FIGURE 1. WASHINGTON NATIONAL OFFSET AZIMUTH SITING

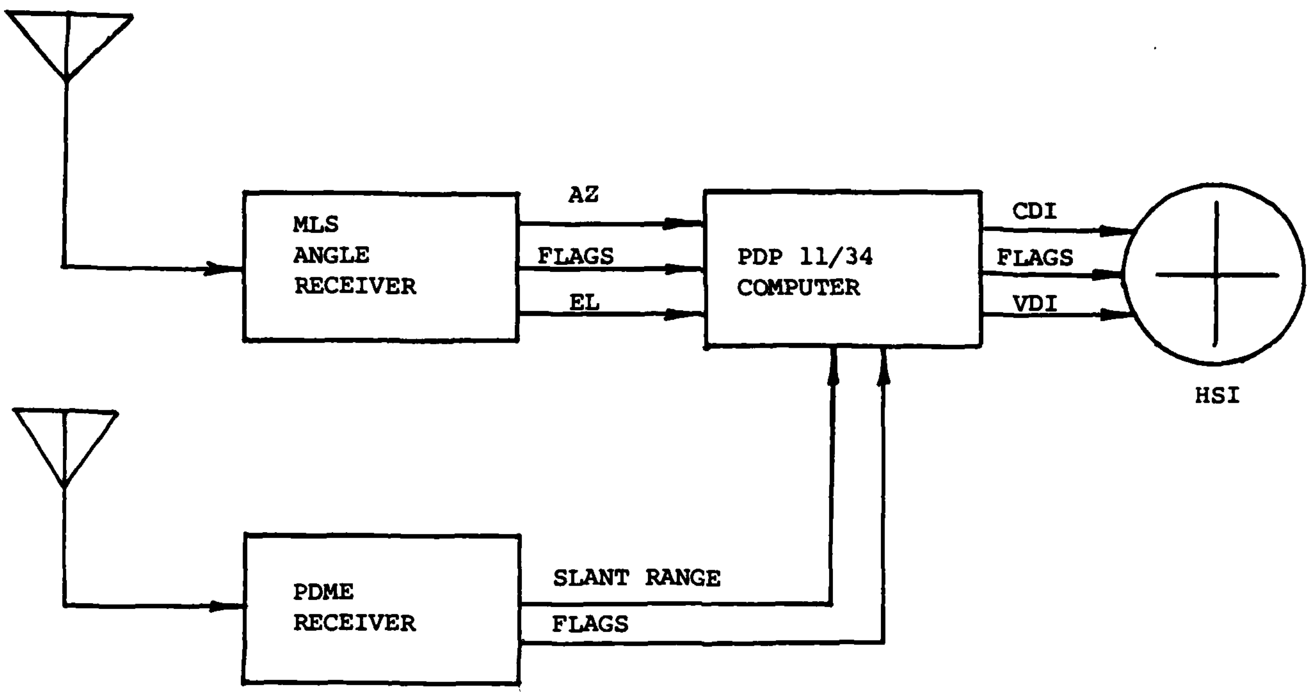
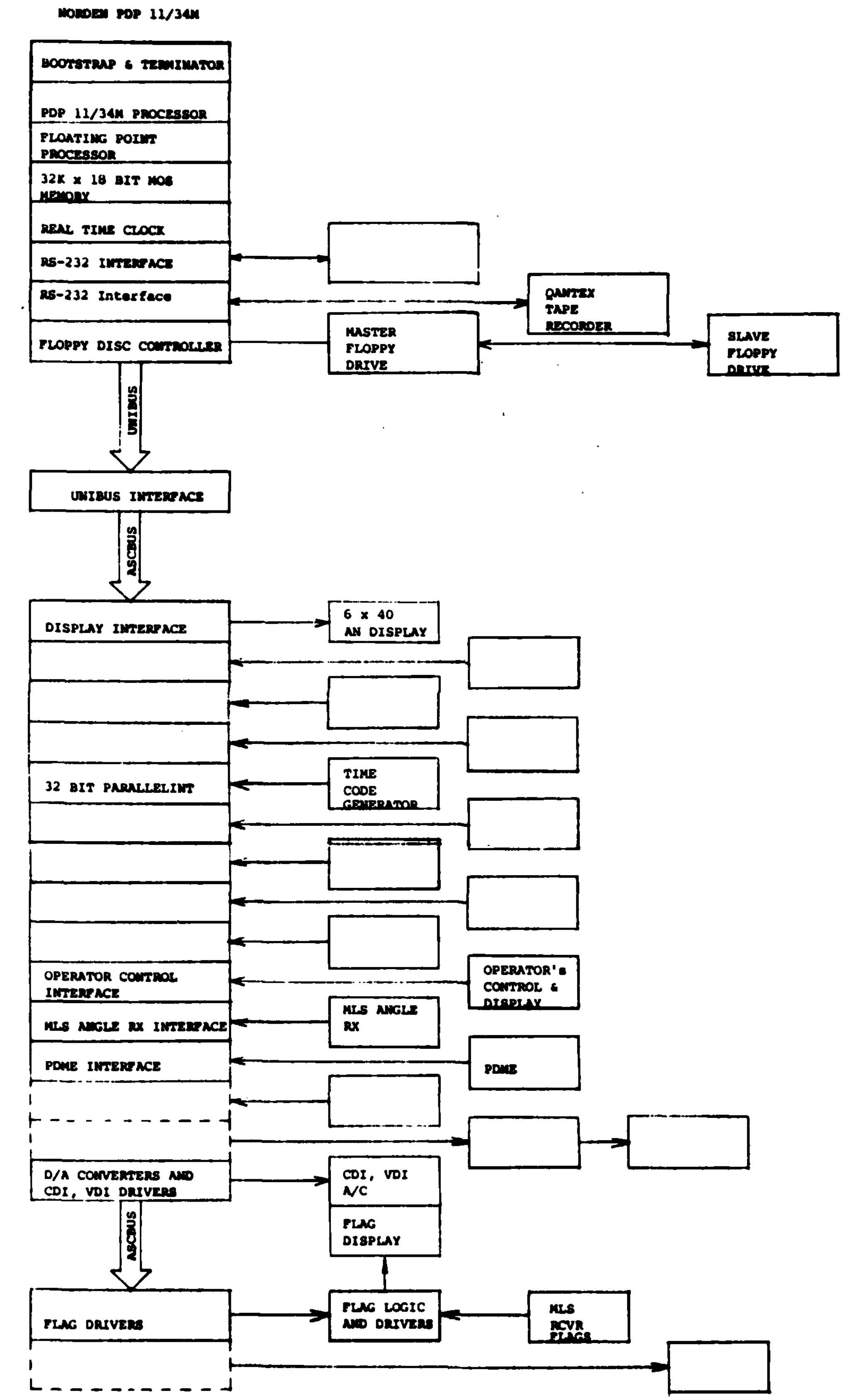


FIGURE 2. SYSTEM DIAGRAM



(1) NOTE: ONLY LABELED SUBSYSTEMS USED FOR PRESENT TESTS

FIGURE 3. MLS COMPUTED CENTERLINE SYSTEM

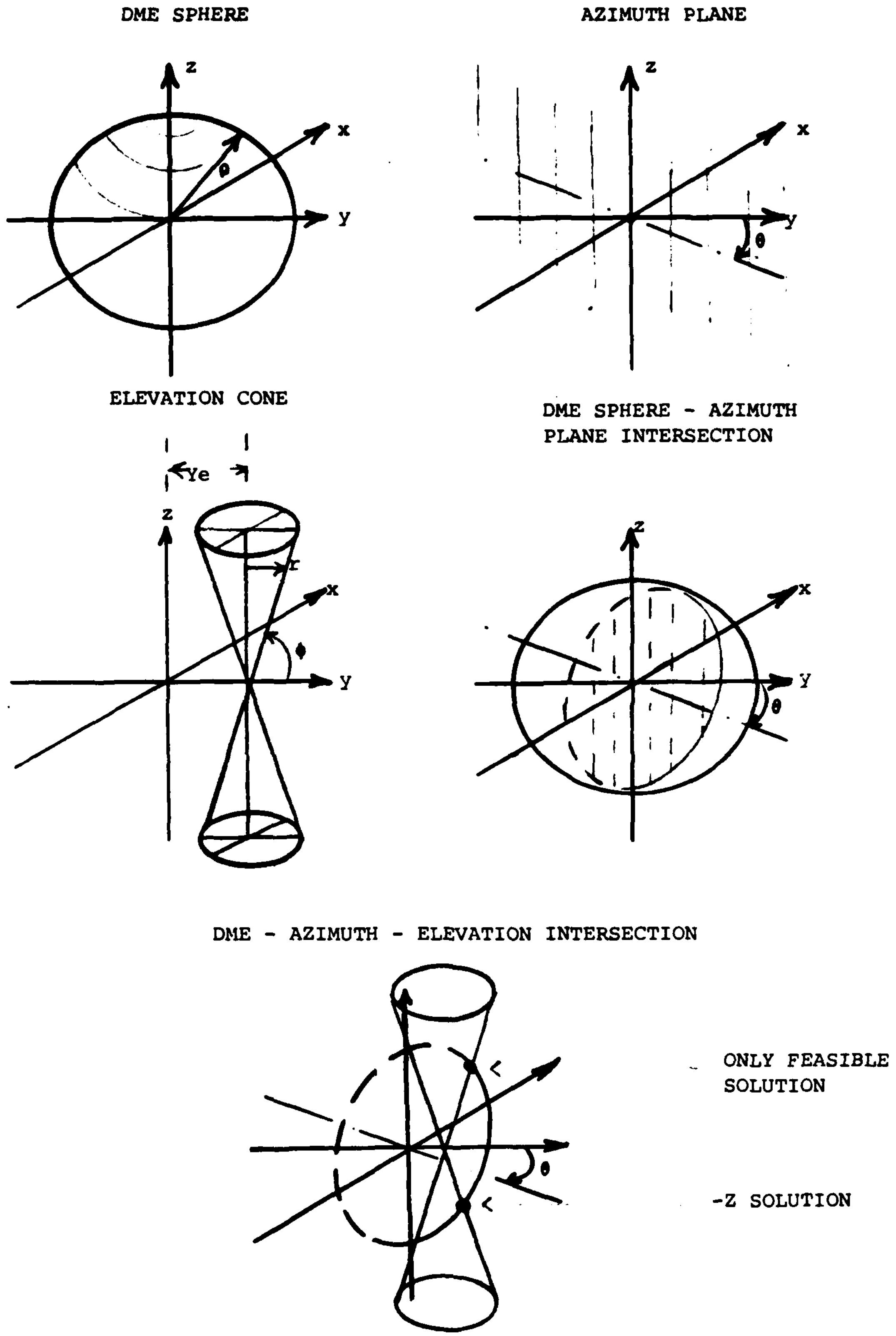


FIGURE 4. GRAPHICAL SOLUTION

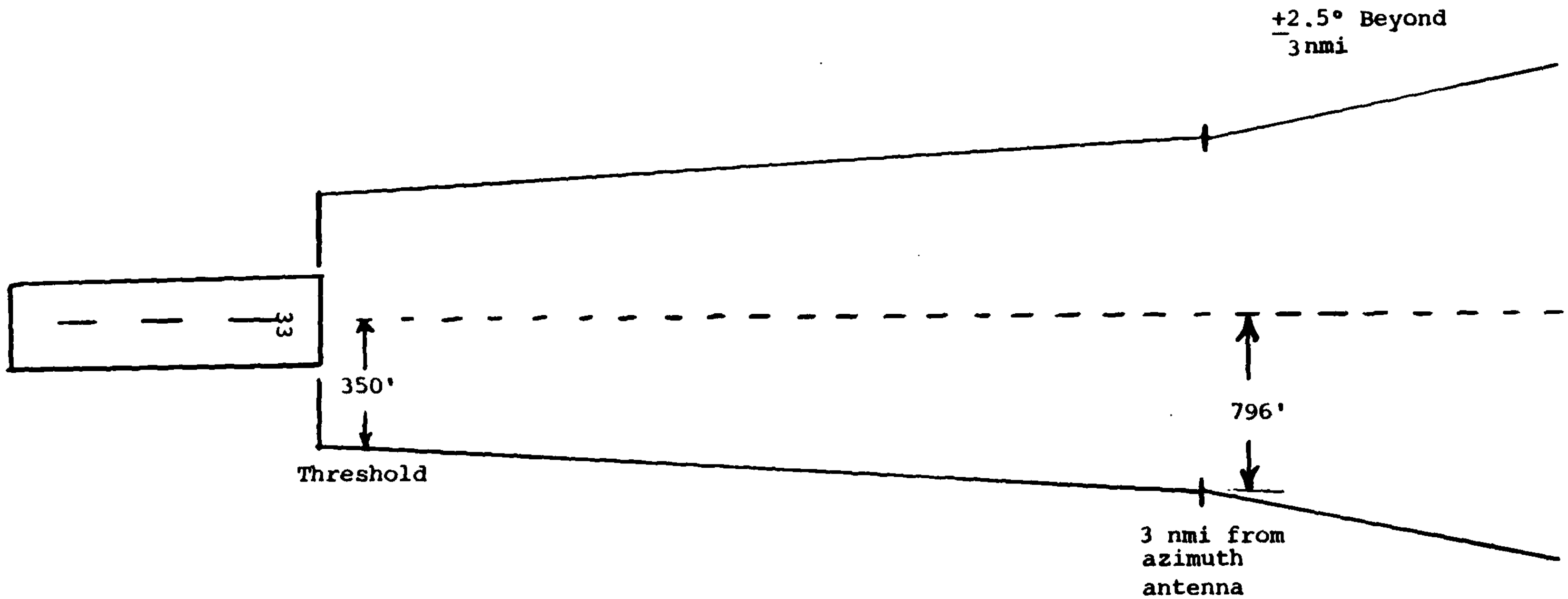


FIGURE 5. COURSE WIDTH TAILORING

```
      SUBROUTINE MLSOFF
C***  COMPUTED CENTERLINE ALGORITHM
C***  BASED ON ALGORITHM BY J. REAMER
C***  CODED 24 JUNE 1985 BY P. SHUSTER
C***  MODIFIED BY J. D'OTTAVI FOR REAL TIME IMPLEMENTATION
C
C     INPUT:
C      DME = RHO IN NAUTICAL MILES AT FULL PRECISION
C      AZ  = THETA IN DEGREES AT FULL PRECISION
C      EL  = PHI IN DEGREES AT FULL PRECISION
C     PARAMETERS:
C      OFFSET TO EL SITE = OFFSET IN FEET (4954.0 FOR DCA)
C      OFFSET TO CENTERLINE = CENTOFF IN FEET (275.0 FOR DCA)
C     COMPUTES:
C      CORRECTED AZIMUTH =THETC IN DEGREES
C     OUTPUTS:
C      STEERING SIGNALS AND FLAGS TO THE HSI
C
C     COMPUTED CENTERLINE ALGORITHM
C     CODED BY B. BILLMANN 20 JUNE 1985
C
C     COMPUTE THE FLAG SIGNAL
C
      IF((IFLAGAZ.EQ.2).OR.(IFLAGAZ.EQ.1)
     1.OR.(IFLAGEL.EQ.2).OR.(IFLAGEL.EQ.1)
     2.OR.(PDMET(1).GE.400)) GO TO 70 !ANY FLAG
C
C     CHECK ANALOG FLAG BITS
C
      IF((IDES(7).AND. '700).NE.'700) GO TO 70
C
C     CONVERT TO RADIANS AND FEET
C
      RHO=PDMEDT(1)*CNMI
      THETA=AZANG*DTR
      PHI=ELANG*DTR
C
C     CHECK FOR WILD POINTS
C
      IF((ELANG.LT..9).OR.(ELANG.GT.20.0)
     1.OR.(RHO.LE.OFFSET)) GO TO 70
      GO TO 100  !INPUT VALID CALCULATE CORRECTION ANGLE
   70 NEWAZ=OLDAZ
      NEWEL=OLDEL
```

FIGURE 6. SOFTWARE LISTING (SHEET 1 OF 3)

```
      IFCTR=IFCTR+1
      IF(IFCTR.LT.ICOAST) GO TO 1000
      IF(IFCTR.GT.ICOAST) IFCTR=ICOAST
      IFLAG=0
      GO TO 1050
C
C     CALCULATE THE SQUARE OF TAN AND COT OF THETA AND PHI
C
  100 TAN2TH=(SIN(THETA)/COS(THETA))*(SIN(THETA)/COS(THETA))
      CT2PHI=(SIN(PHI)/COS(PHI))*(SIN(PHI)/COS(PHI))
C
C     DETERMINE QUADRATIC PARAMETERS A,B,C
C
      A=1+TAN2TH+CT2PHI+CT2PHI*TAN2TH
      B=-2*OFFSET
      C=-RHO*RHO*CT2PHI+OFFSET*OFFSET
C
C     SOLVE QUADRATIC AND PICK LARGER SOLUTION
C     Y = DISTANCE TO GO
C
      Y=-B+SQRT(B*B-4*A*C)
      Y=Y/(2*A)
C
C     COMPUTE CORREWCTION ANGLE THETR
C
      THETR=ATAN(CENTOFF/Y)
C
C     COMPUTE ANGLE TO BE DISPLYED
C
      THETC=THETA+THETR
C
C     COMPUTE AZ COURSE WIDTH GAIN SCHEDULE
C
      S=1.0
      IF(Y.LE.3.0) S=-.59*(Y-3.0) + 1.0
C
C     CONVERT STEERING SIGNALS TO D TO A UNITS
C
      TEMP=THETC*RFSAZ/S
      IF(ABS(TEMP).LT. 32767.0) GO TO  900
      TEMP=SIGN(32767.0,TEMP)
 900  NEWAZ=TEMP
      TEMP=(PHI-ELREF)*RFSEL
      IF(ABS(TEMP).LT.32767.0) GO TO 910
      TEMP=SIGN(32767.0,TEMP)
 910  NEWEL=TEMP
```

FIGURE 6. SOFTWARE LISTING (SHEET 2 OF 3)

```
      IFLAG = 3  !PULL BOTH FLAGS FROM VIEW
      IFCTR = 0  !RESET COAST COUNTER
      OLDAZ=NEWAZ
      OLDEL=NEWEL
C
C     OUPUT TO D/A CONVERTERS
C
 1000 CALL DAOUT(0,-NEWAZ) !DRIVE THE LATERAL NEEDLE
      CALL DAOUT(1,NEWEL)  !DRIVE THE VERTICAL NEEDLE
 1050 CALL FOUT(IFLAG)     !SET THE FLAGS
      RETURN
      END
```

FIGURE 6. SOFTWARE LISTING (SHEET 3 OF 3)

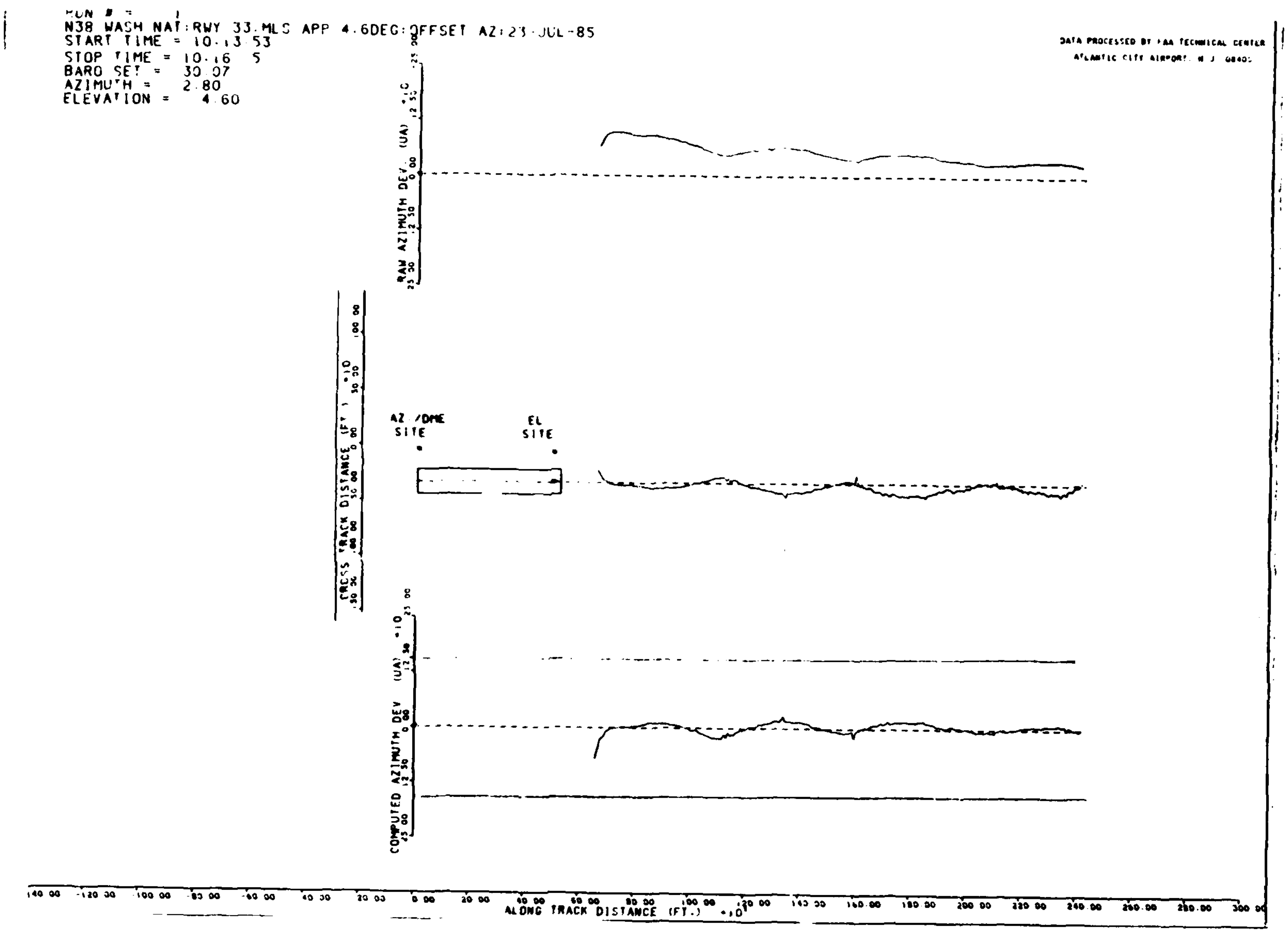


FIGURE 7. RUN 1: CROSSTRACK INFORMATION

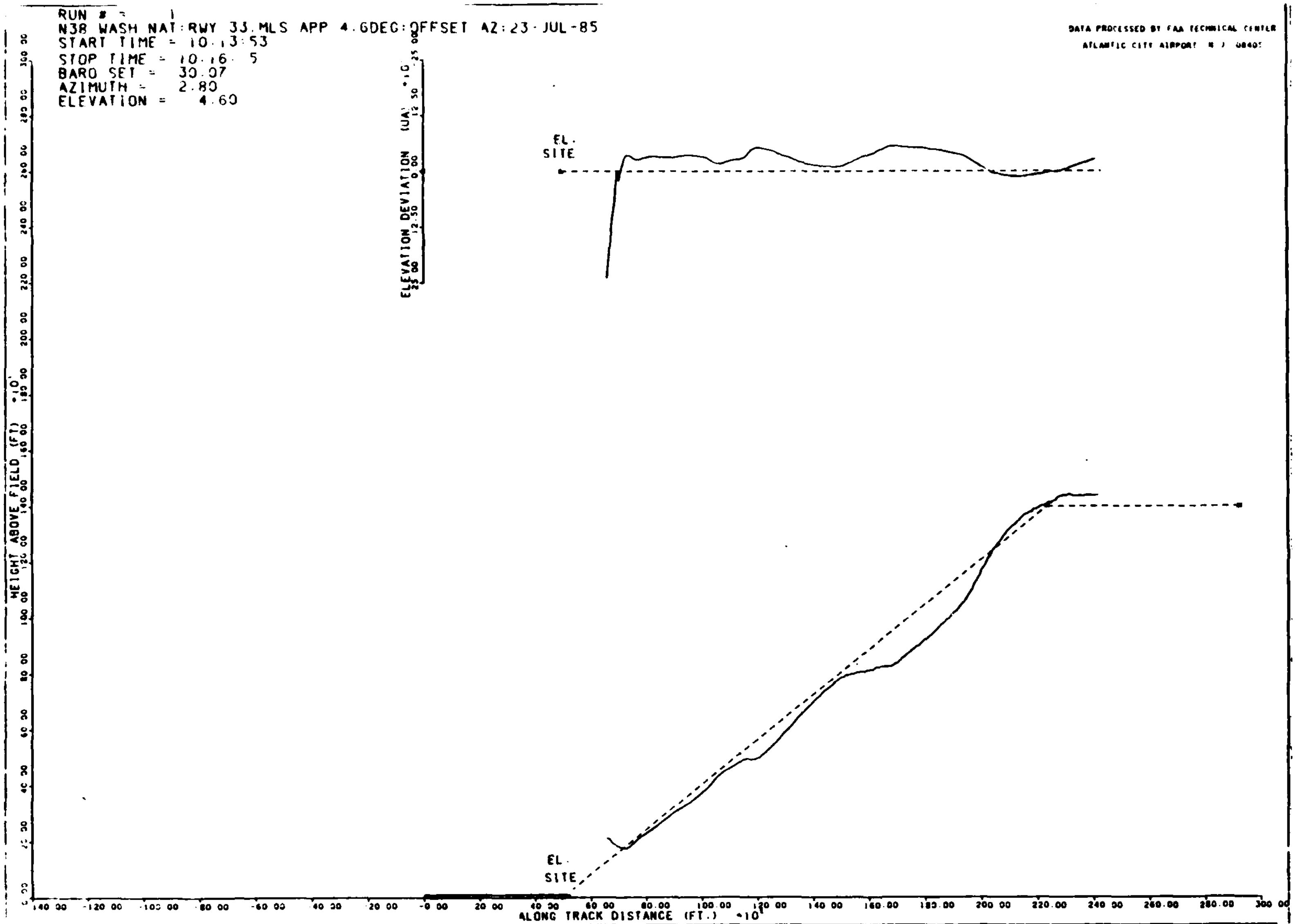


FIGURE 8. RUN 1: ELEVATION INFORMATION

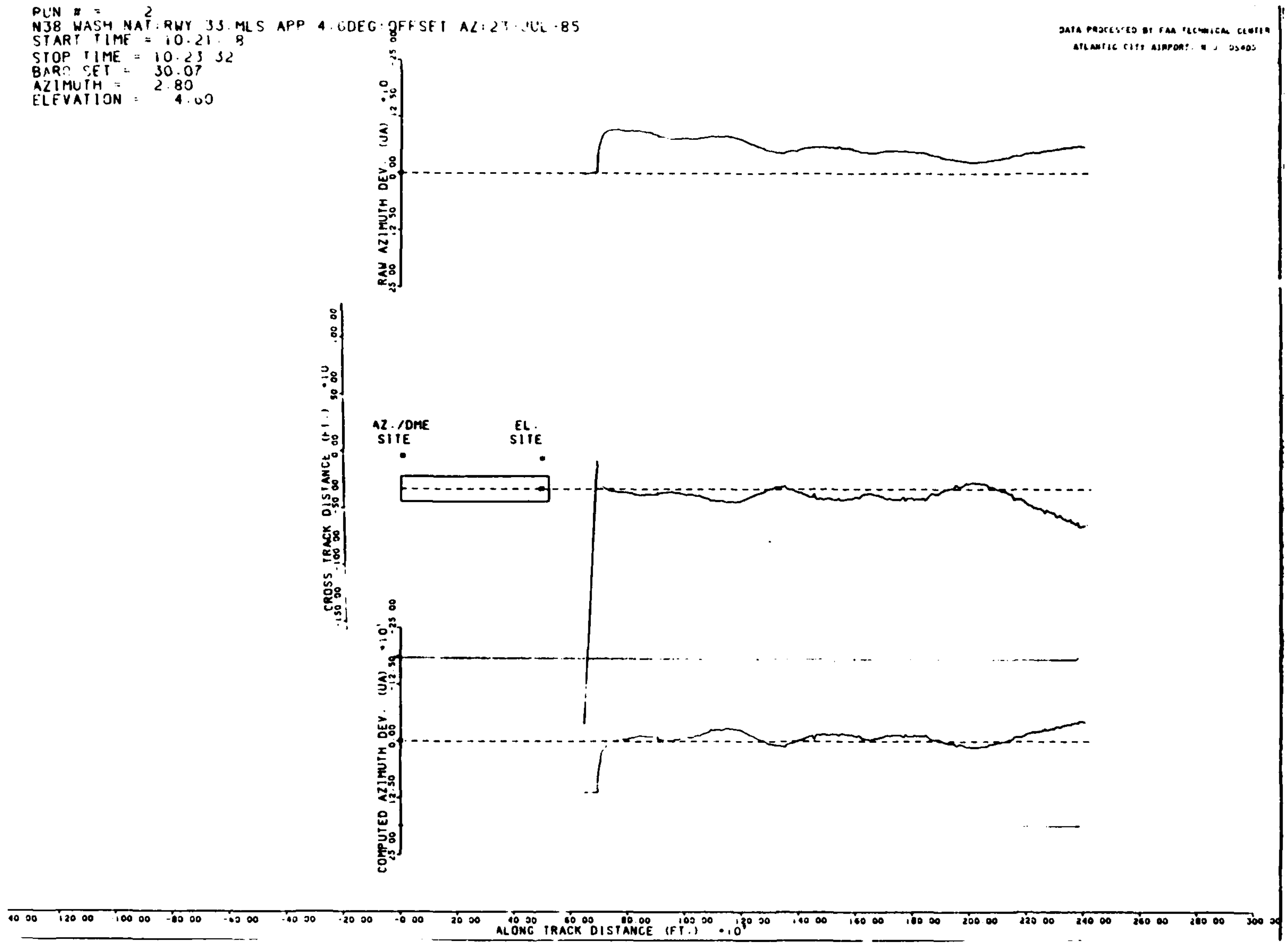


FIGURE 9. RUN 2: CROSSTRACK INFORMATION

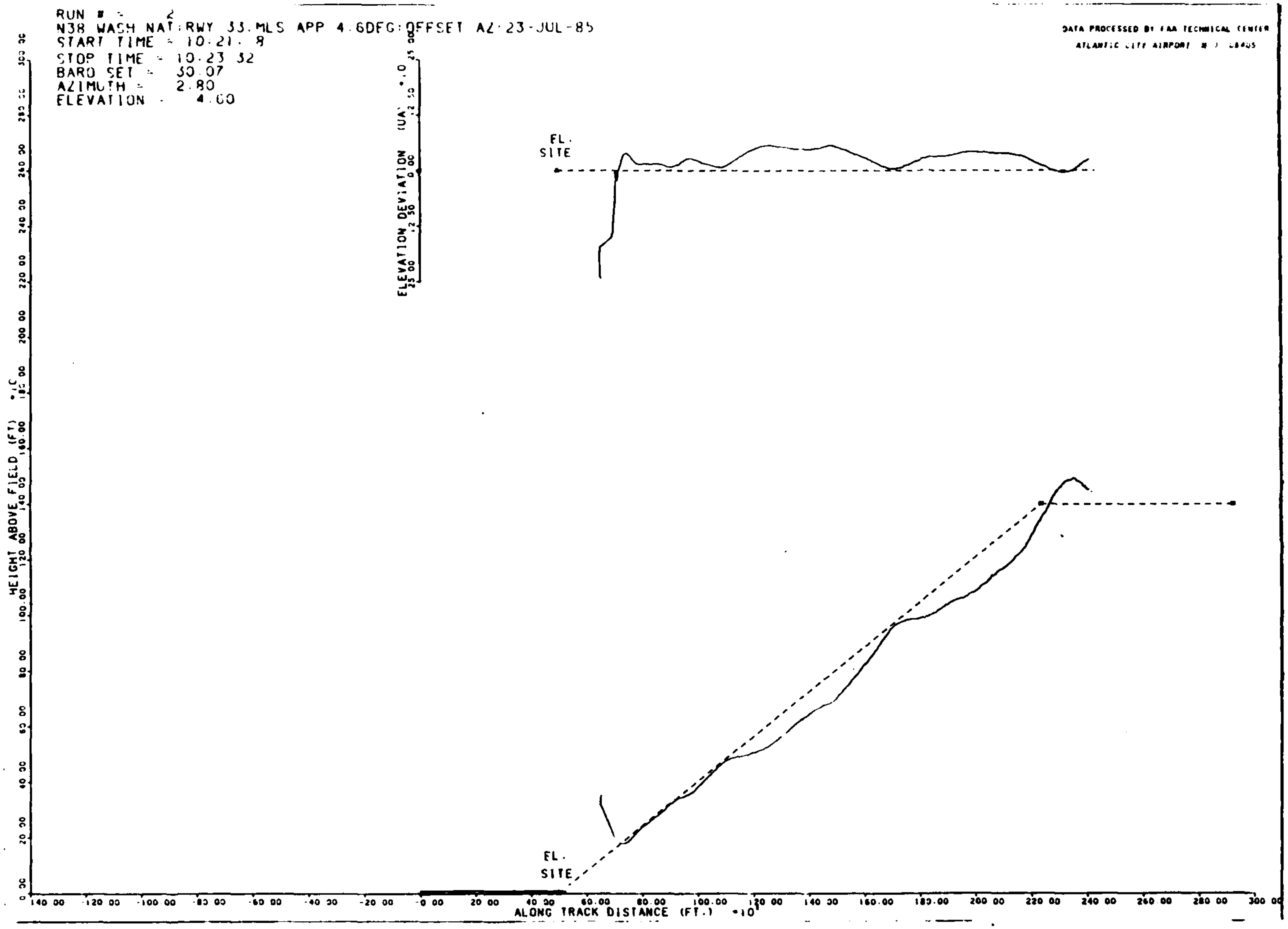


FIGURE 10. RUN 2: ELEVATION INFORMATION

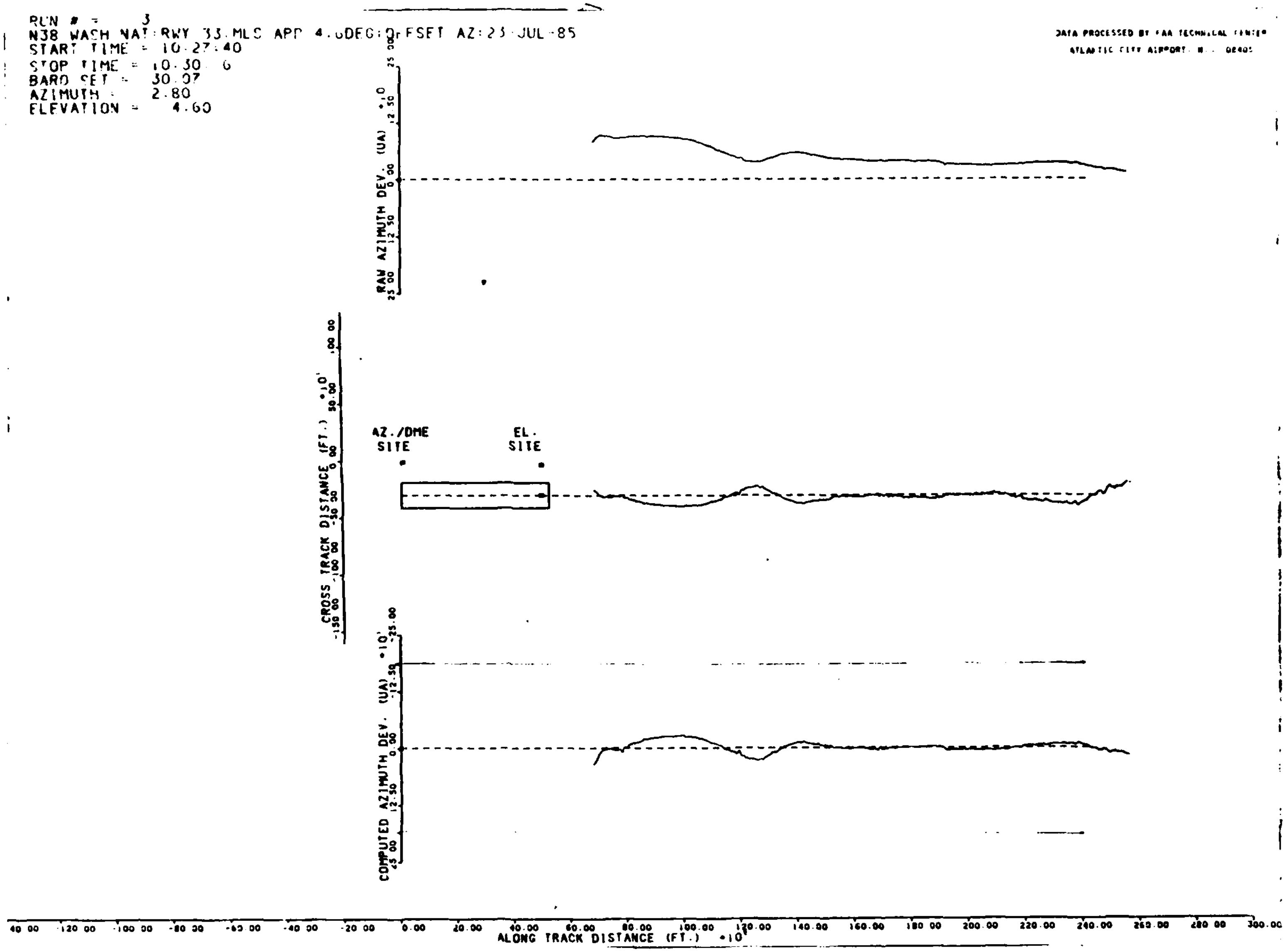


FIGURE 11. RUN 3: CROSSTRACK INFORMATION

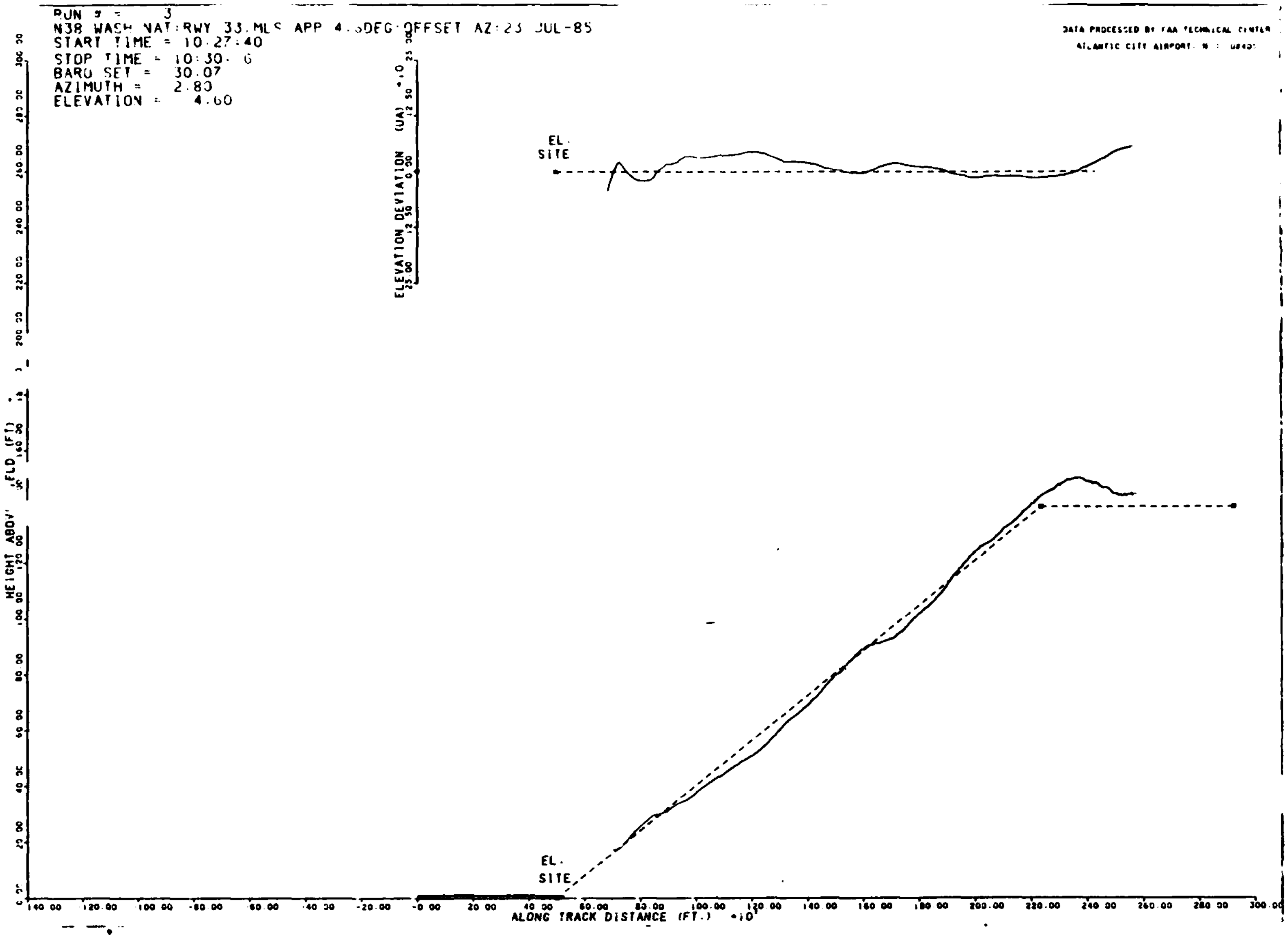


FIGURE 12. RUN 3: ELEVATION INFORMATION

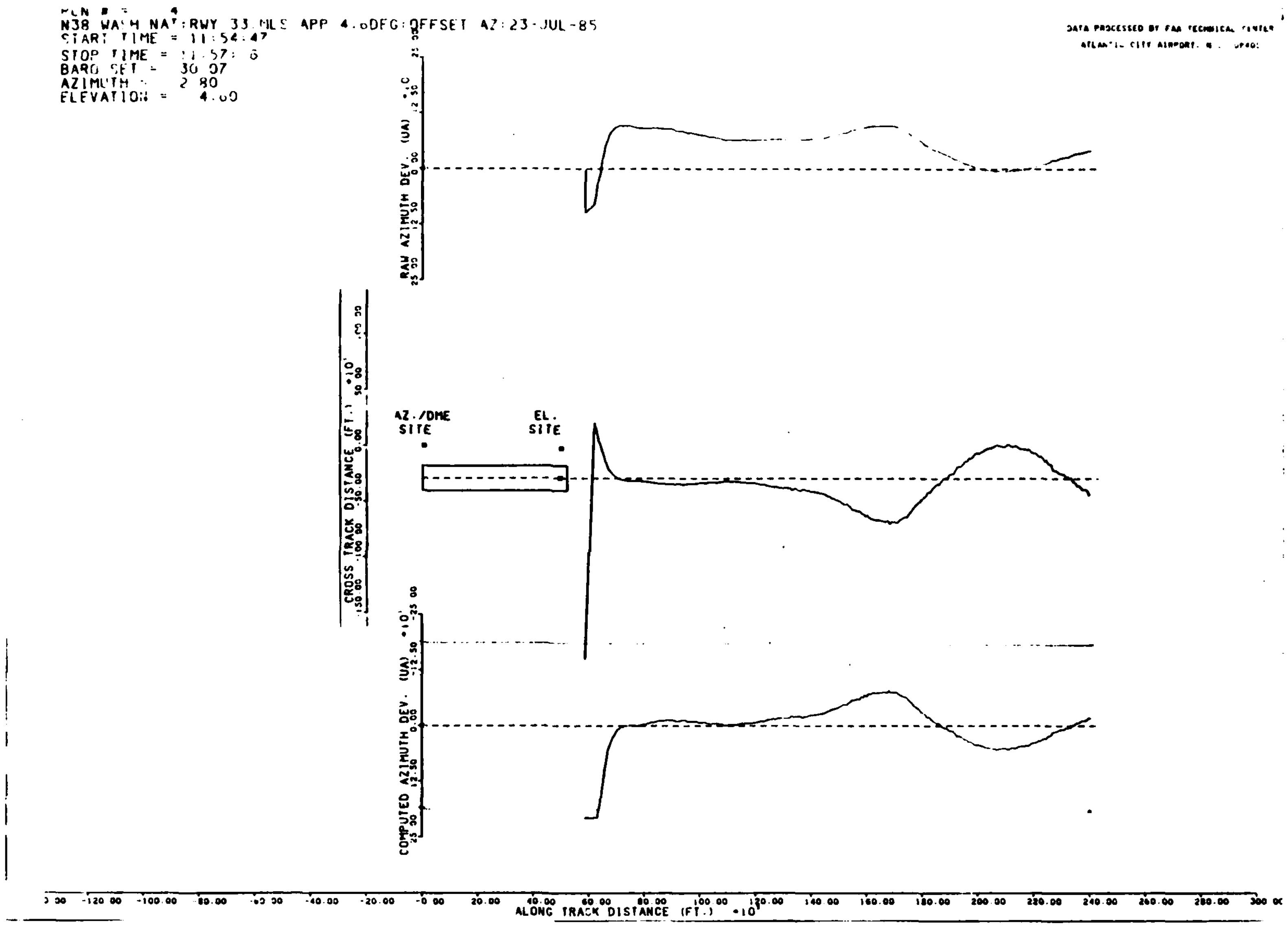


FIGURE 13. RUN 4: CROSSTRACK INFORMATION

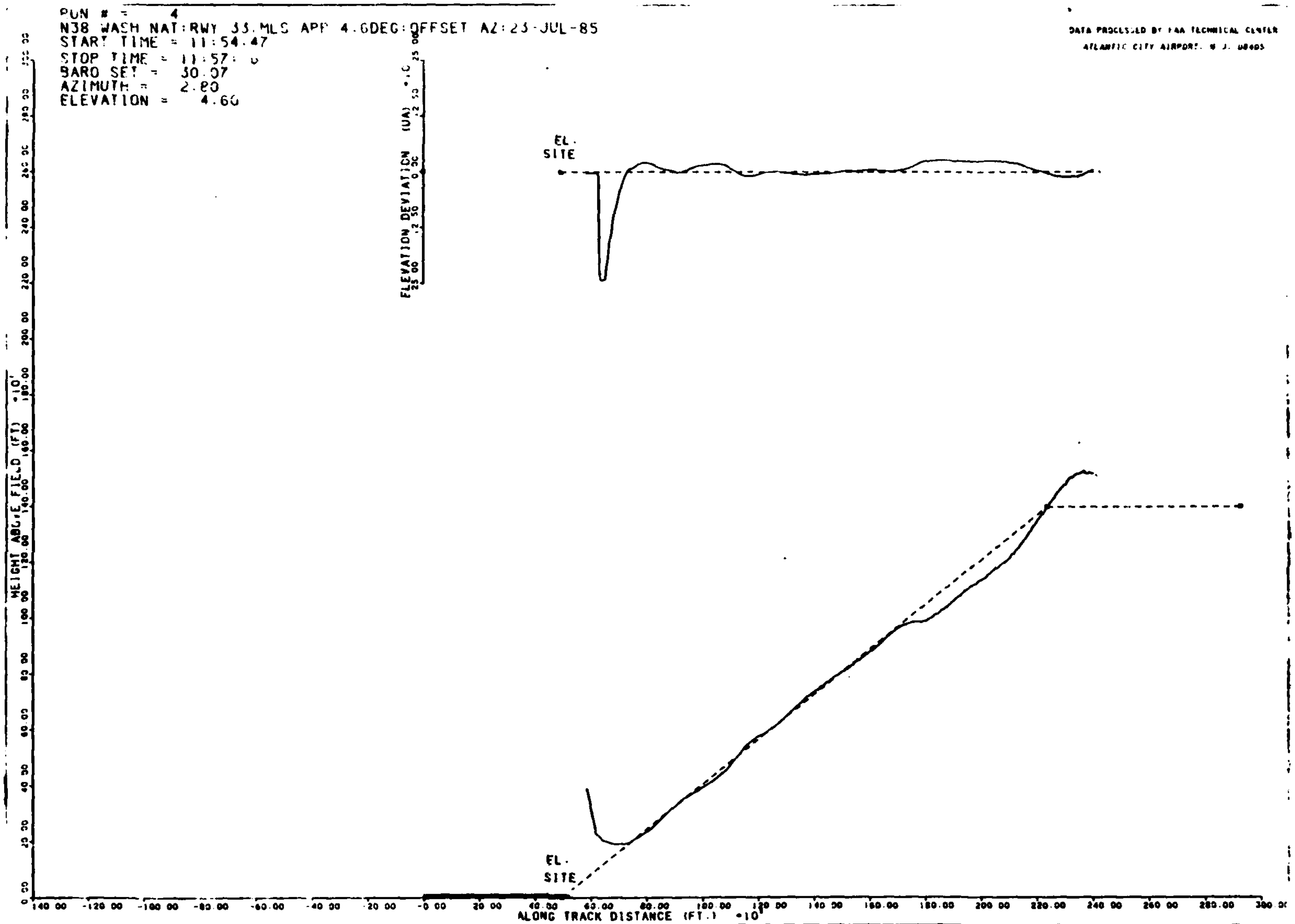


FIGURE 14. RUN 4: ELEVATION INFORMATION

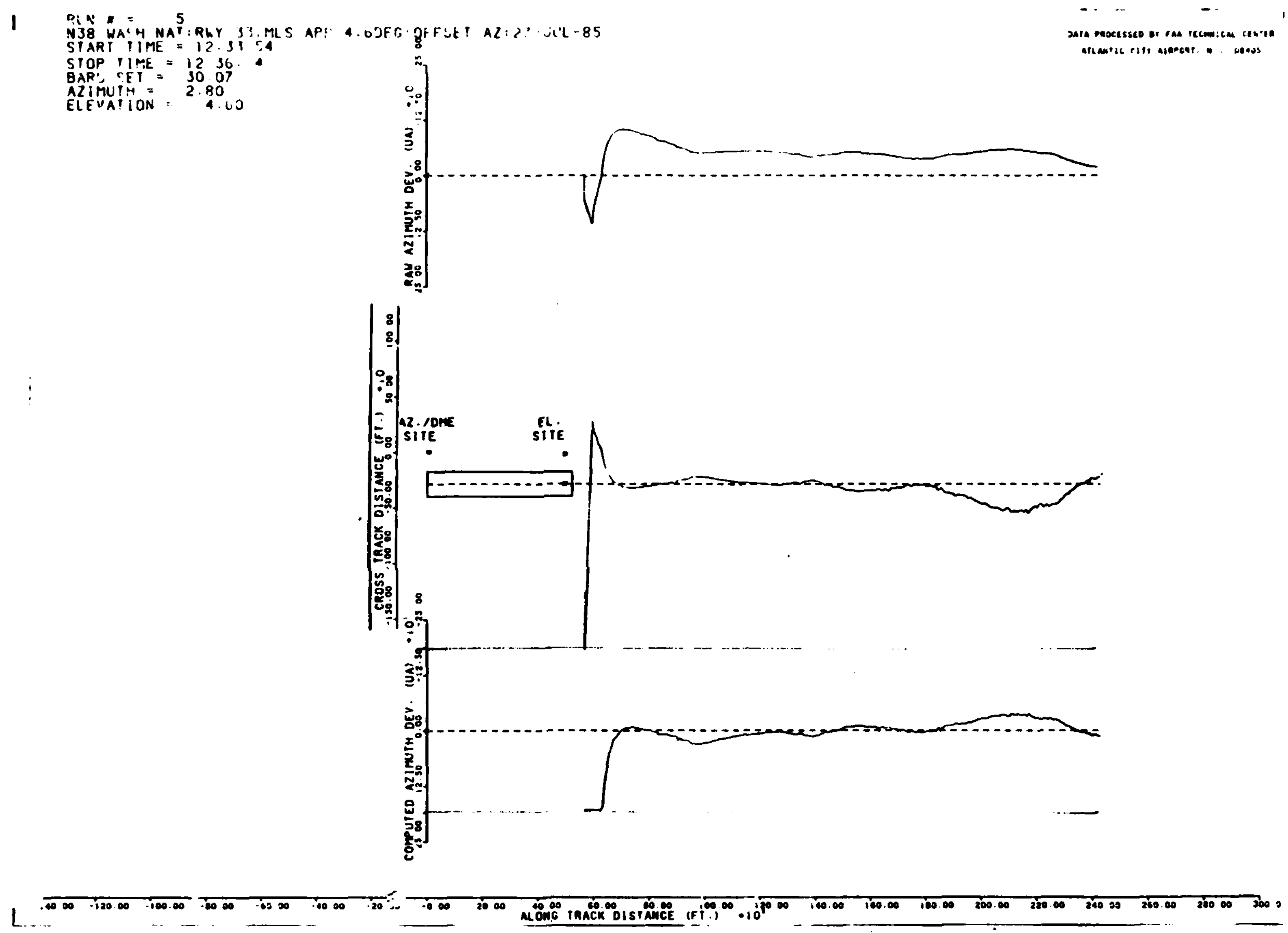


FIGURE 15. RUN 5: CROSSTRACK INFORMATION

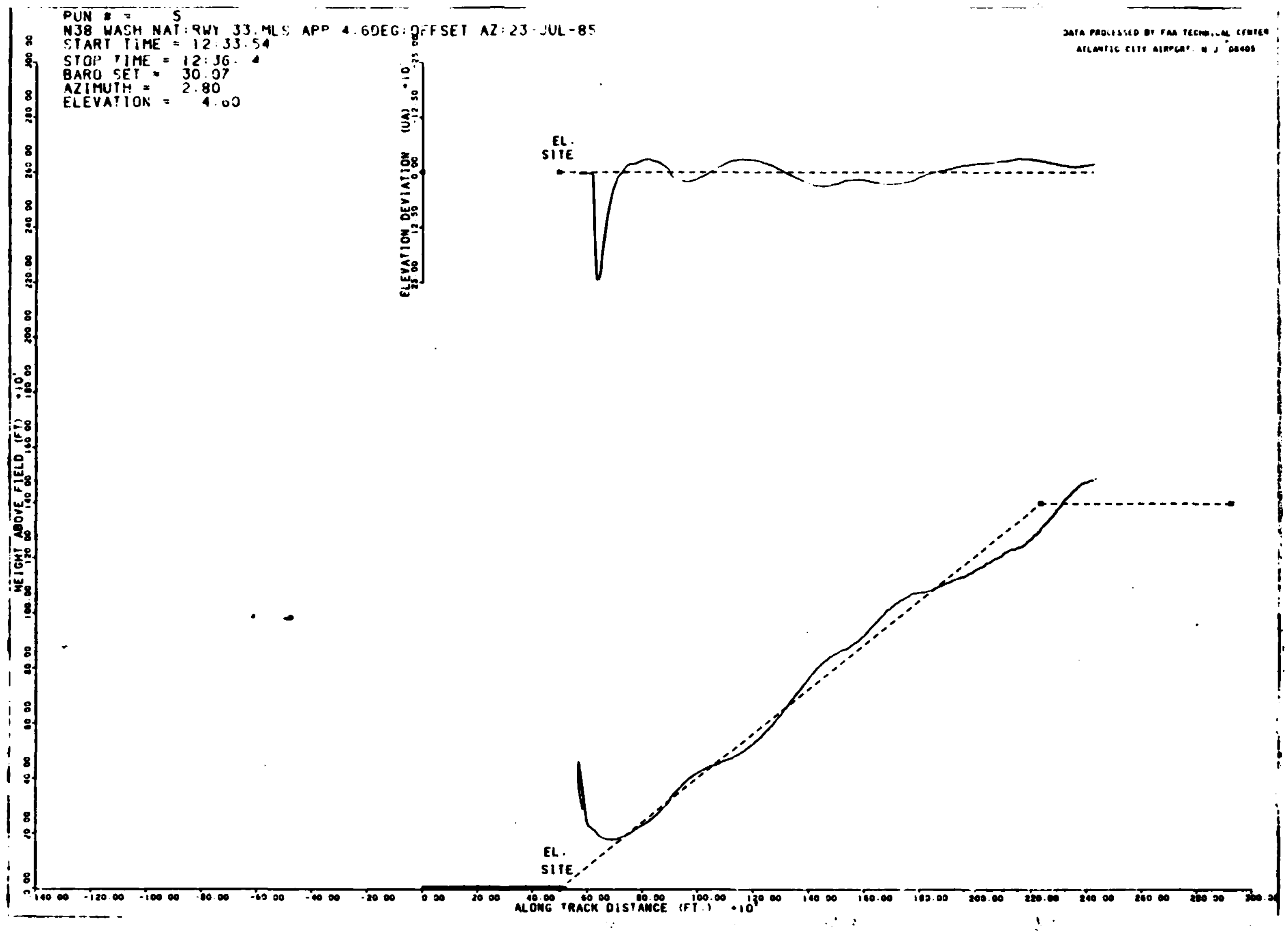


FIGURE 16. RUN 5: ELEVATION INFORMATION

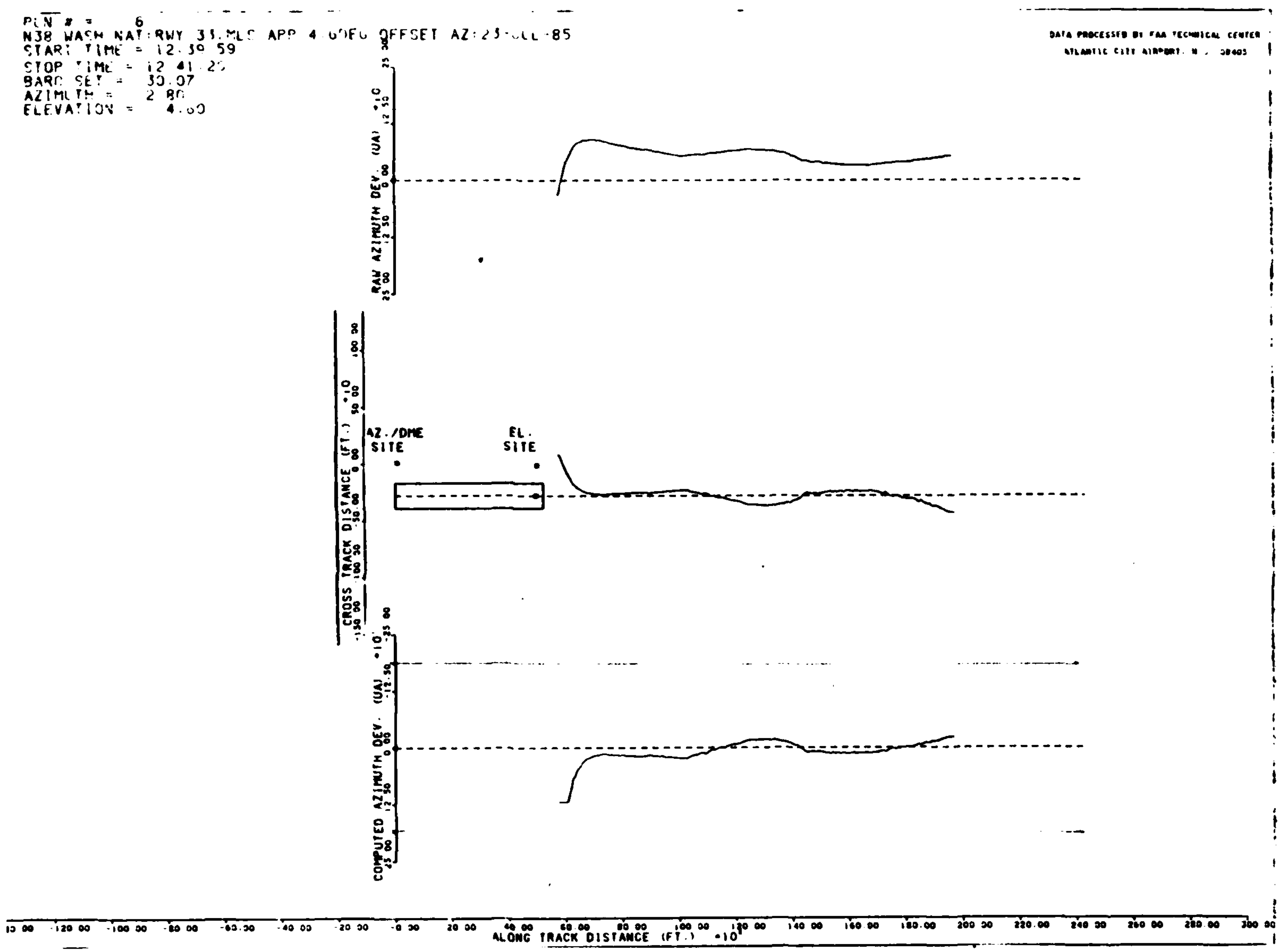


FIGURE 17. RUN 6: CROSSTRACK INFORMATION

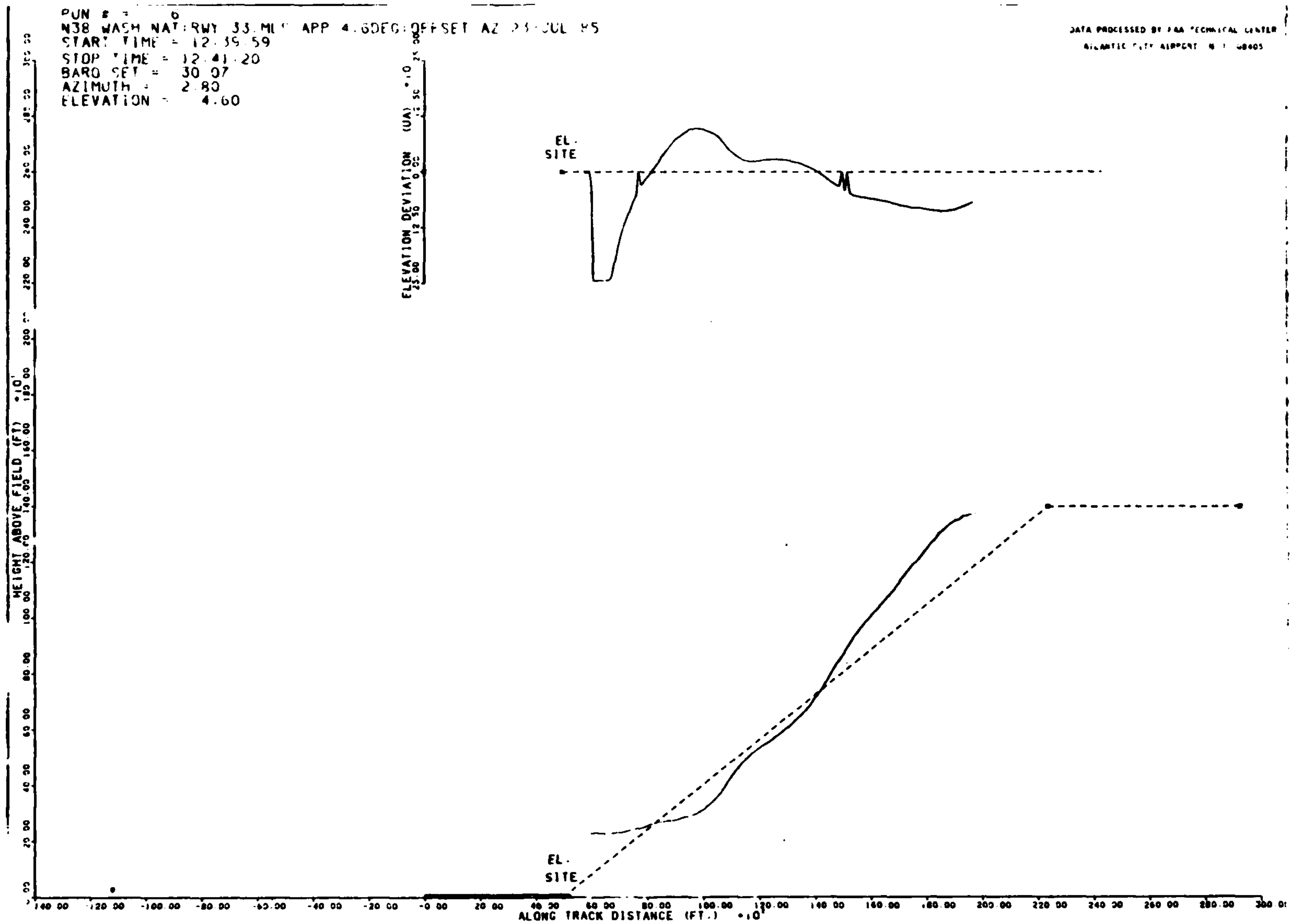


FIGURE 18. RUN 6: ELEVATION INFORMATION

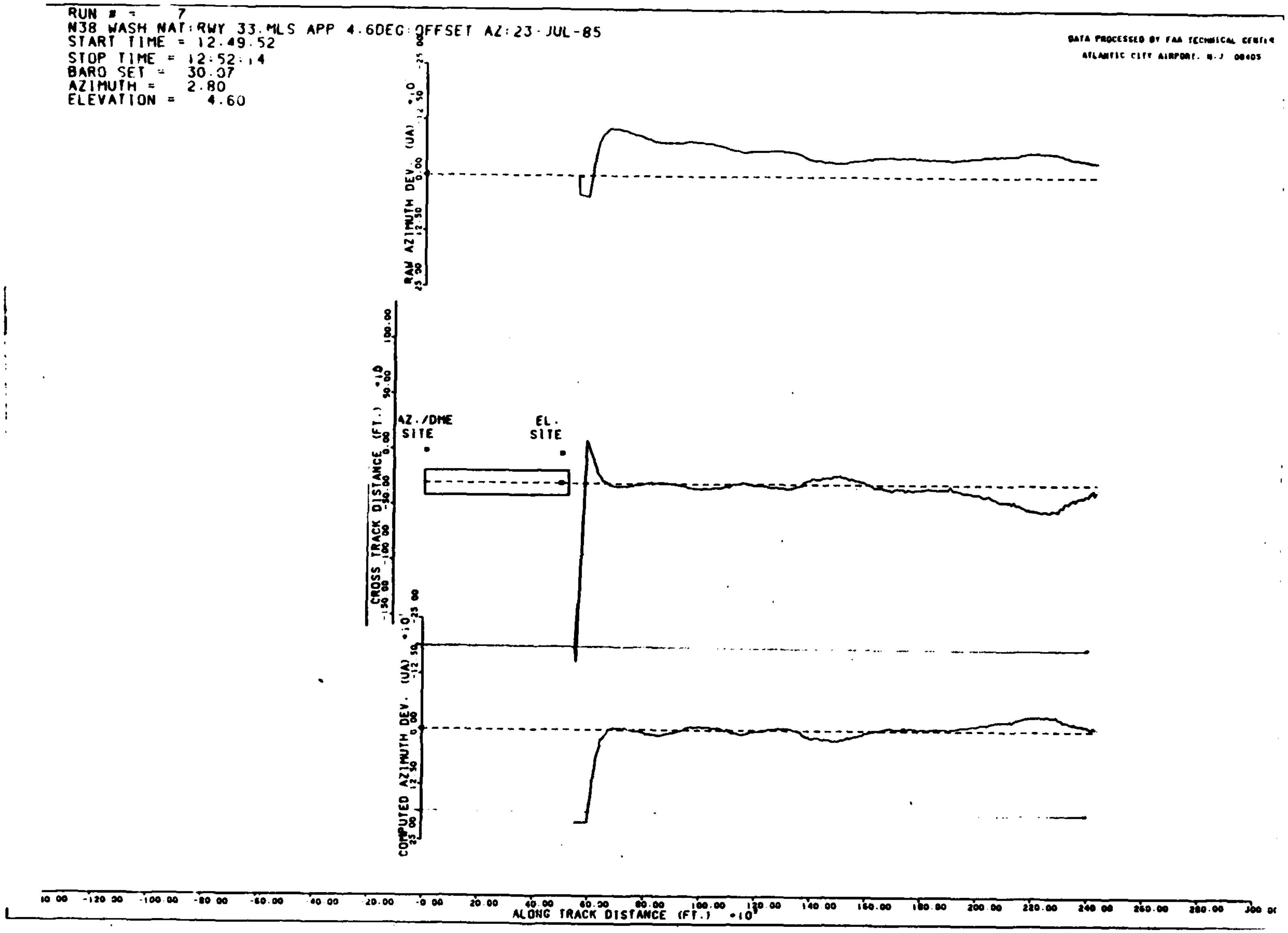


FIGURE 19. RUN 7: CROSSTRACK INFORMATION

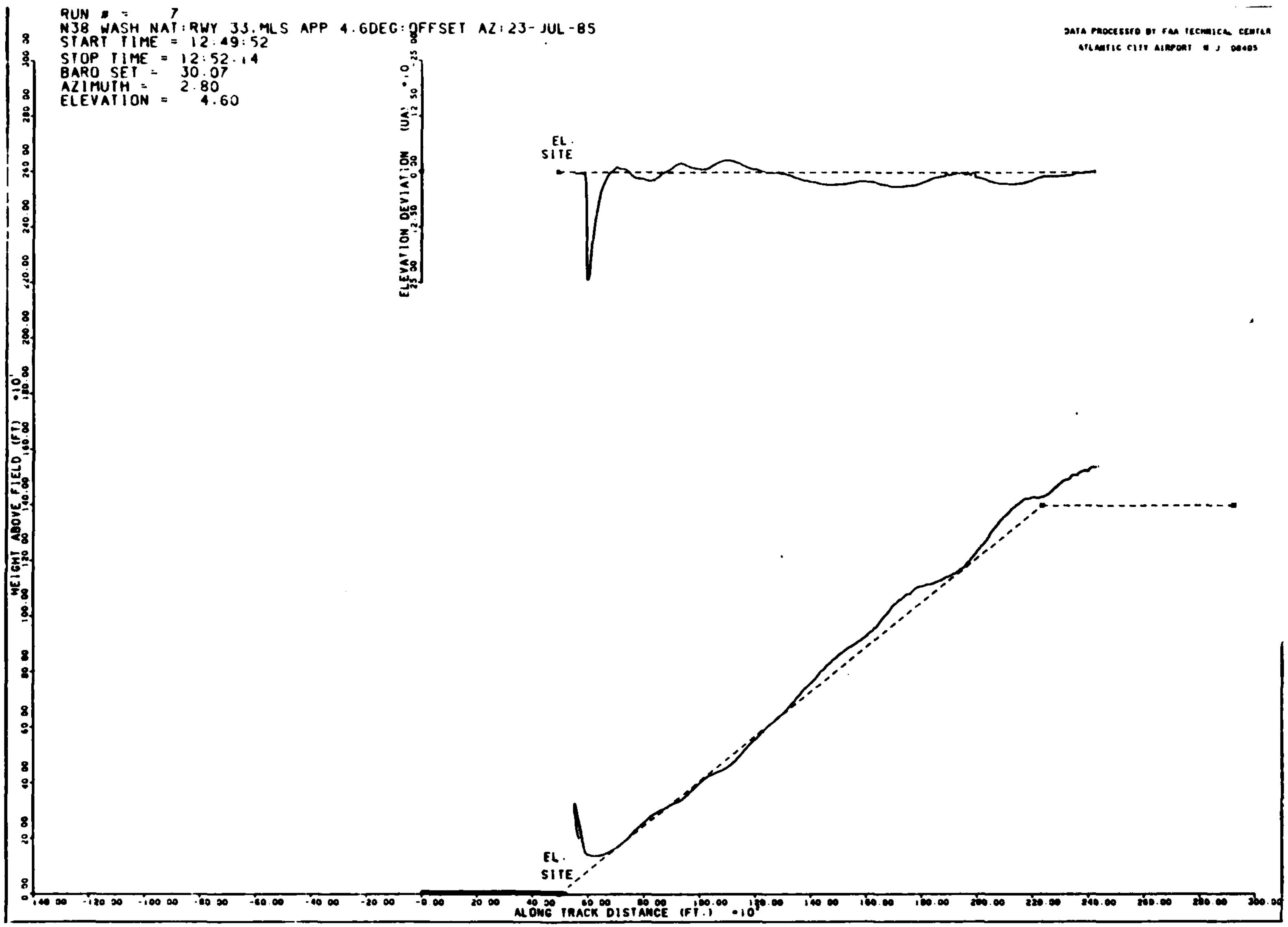


FIGURE 20. RUN 7: ELEVATION INFORMATION

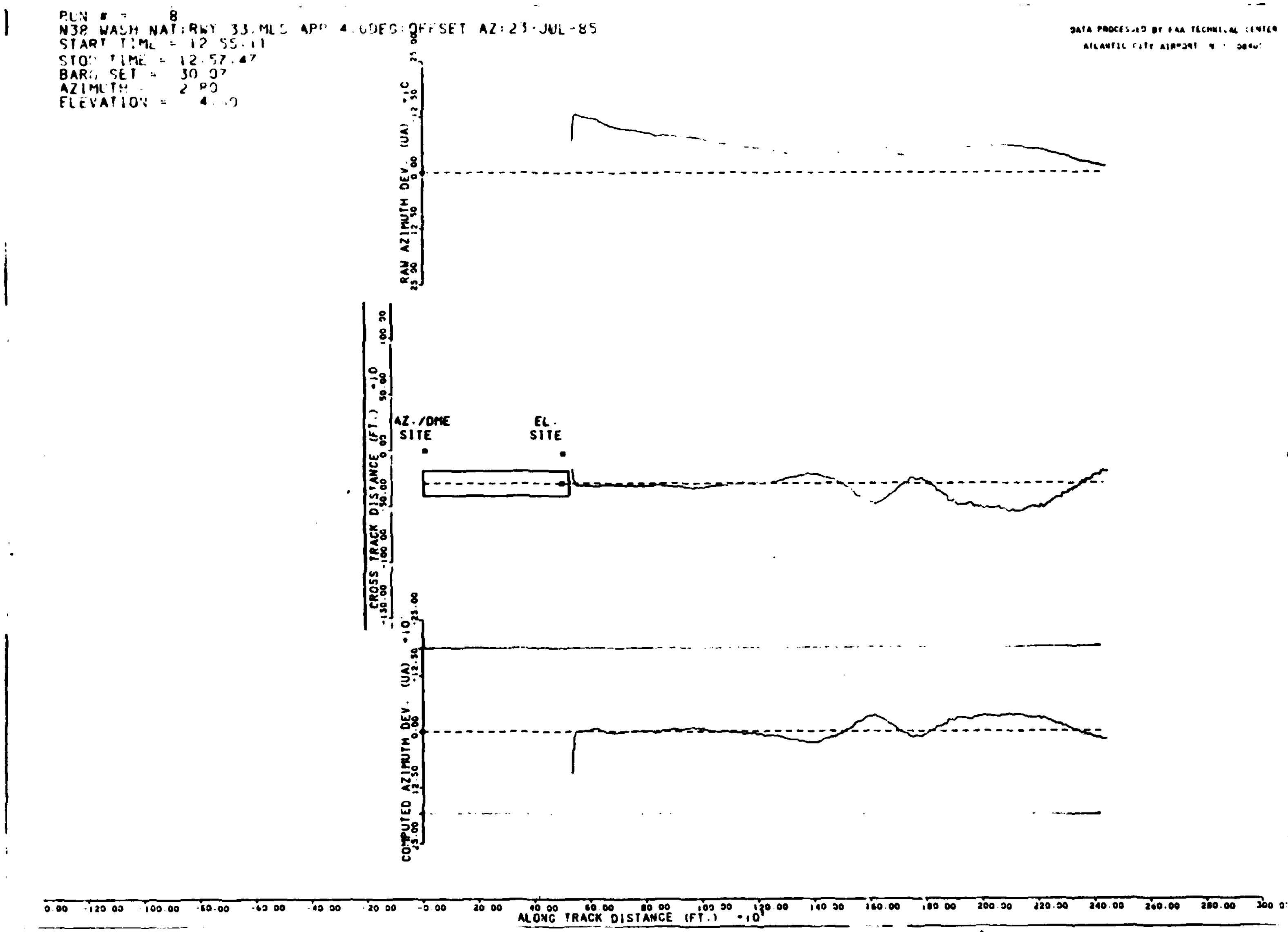


FIGURE 21. RUN 8: CROSSTRACK INFORMATION

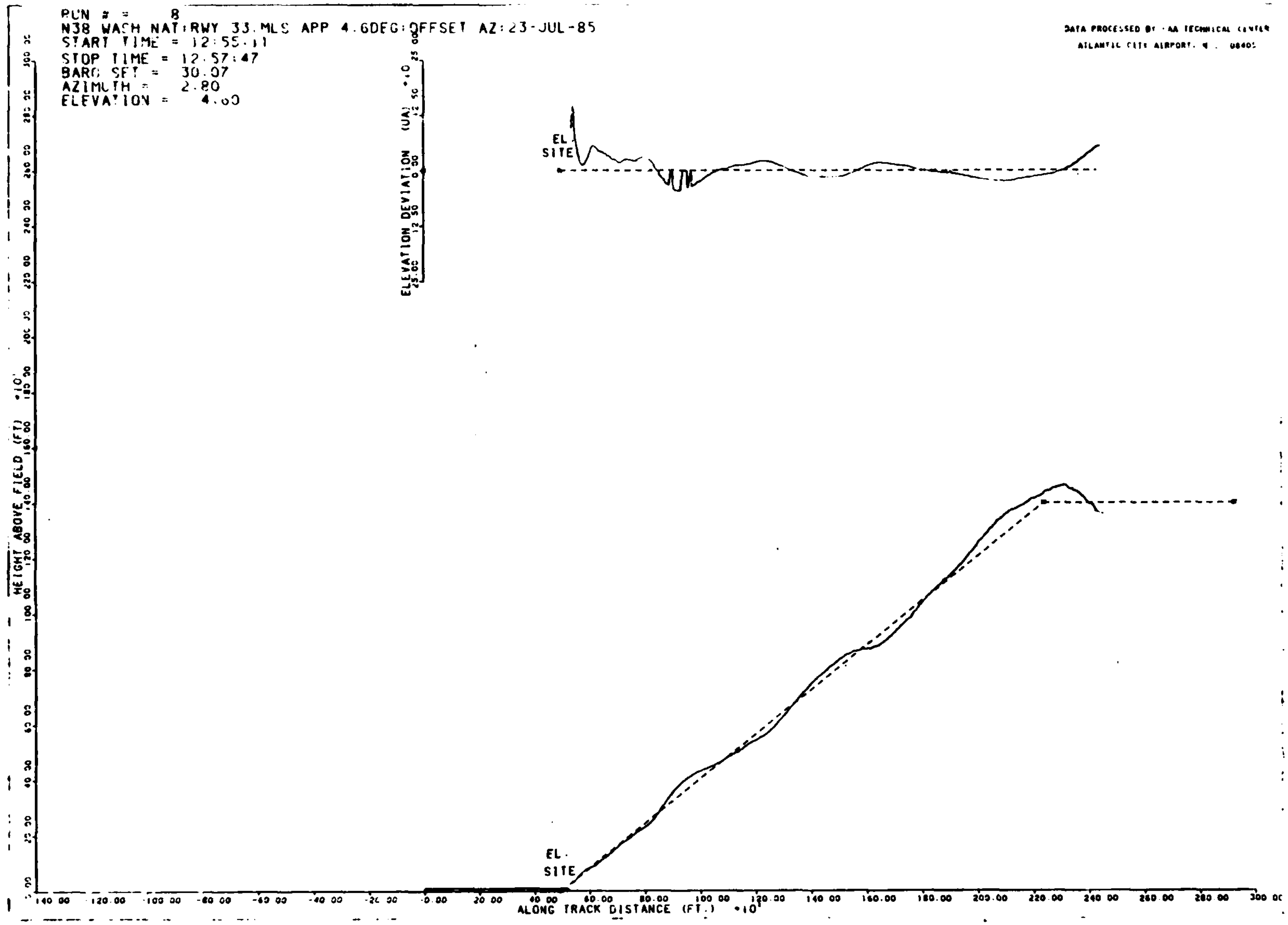


FIGURE 22. RUN 8: ELEVATION INFORMATION

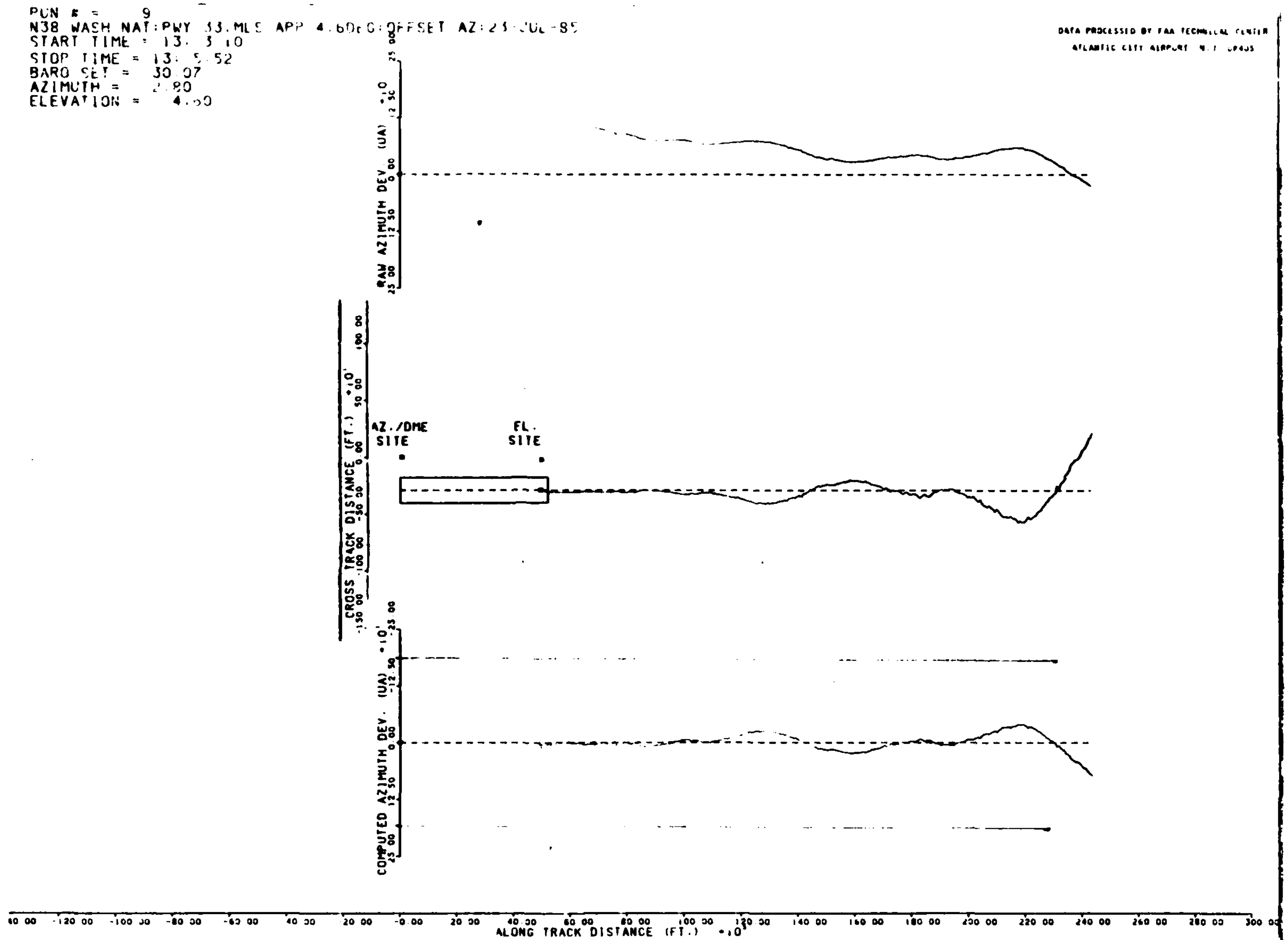


FIGURE 23. RUN 9: CROSSTRACK INFORMATION

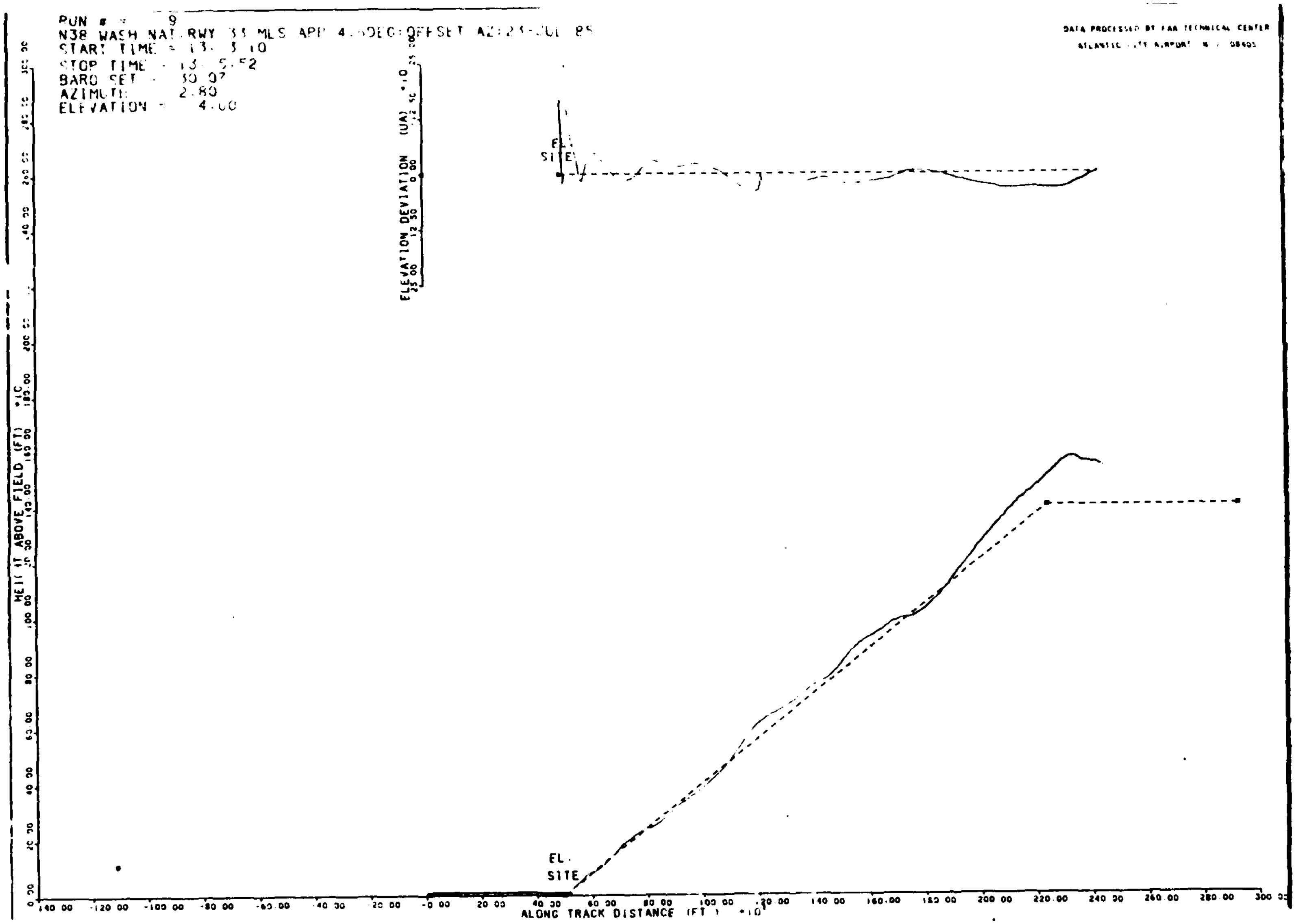


FIGURE 24. RUN 9: ELEVATION INFORMATION

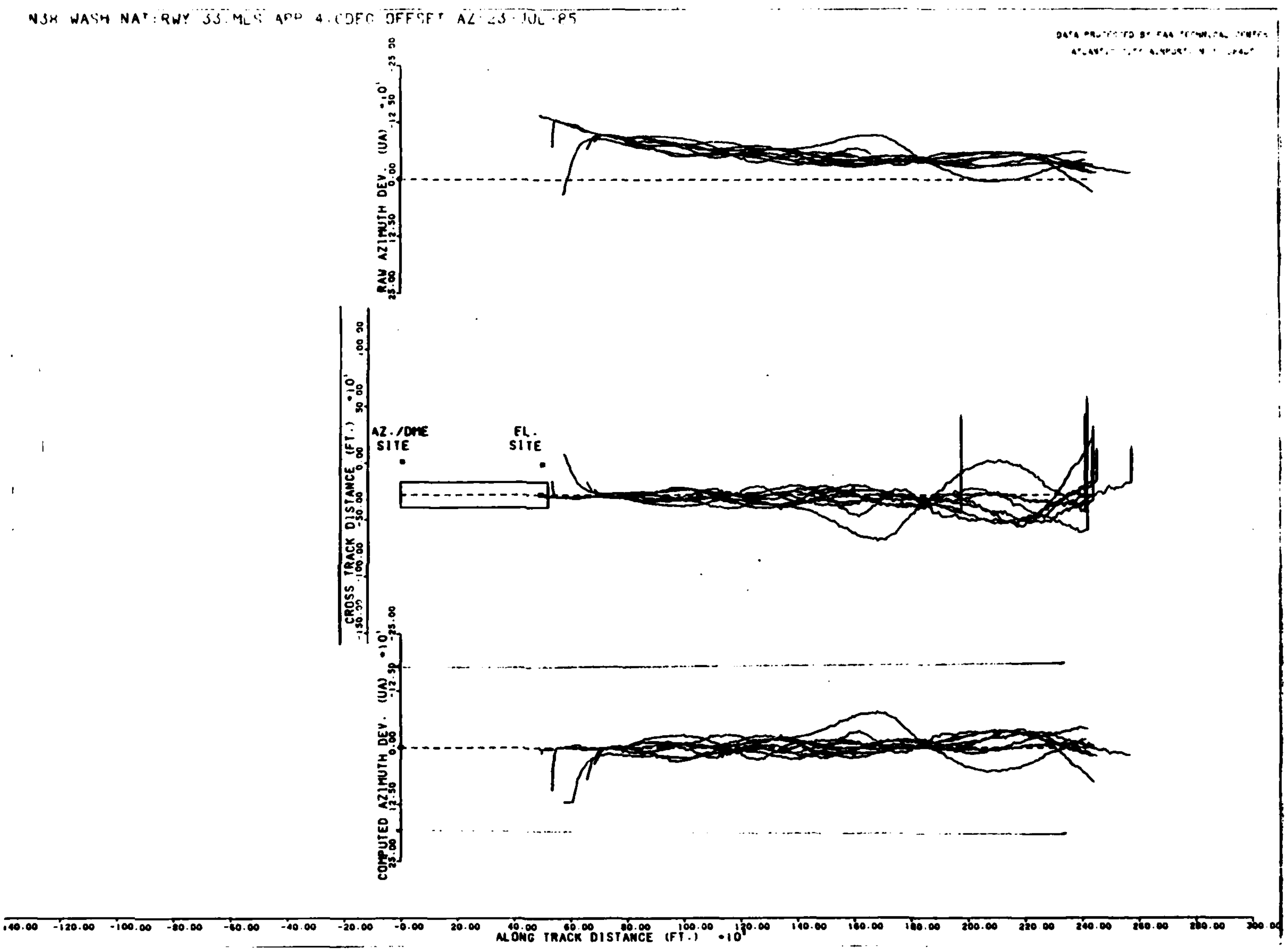


FIGURE 25. COMPOSITE CROSSTRACK INFORMATION

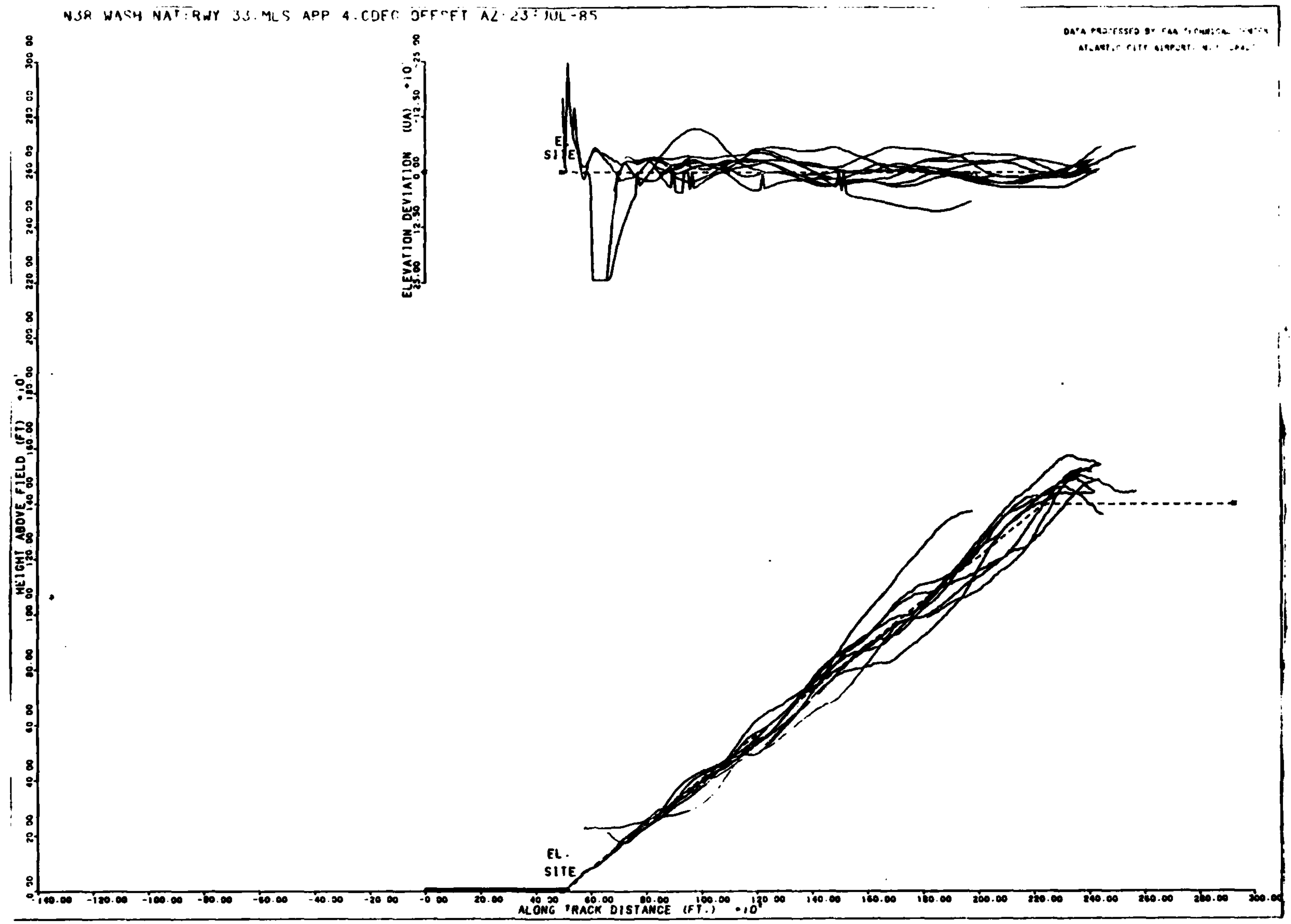


FIGURE 26. COMPOSITE ELEVATION INFORMATION

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